World Renewable Energy Congress – Sweden

8–13 May, 2011
Linköping, Sweden

Editor

Professor Bahram Moshfegh

Linköping Electronic Conference Proceedings, 57
Linköping University Electronic Press
Linköping, Sweden, 2011

http://www.ep.liu.se/ecp_home/index.en.aspx?issue=057
ISBN: 978-91-7393-070-3
ISSN 1650-3740 (online)
ISSN 1650-3686 (print)

Volume 13

Sustainable Transport

Table of Contents

The Use of Sustainable Travel Planning Strategies within Remote Cities

Mohamed H Ismail[1]

[1] *Technologies for Sustainable Built Environments Centre, University of Reading, United Kingdom and Hereford Futures Limited, Hereford, United Kingdom*
** Corresponding author. Tel: +447912044831 E-mail: Mohamed@herefordfutures.co.uk*

Abstract: The paper considers sustainable travel strategies for remote cities that form a regional centre for a wider area. The strategies aim to minimise private vehicle traffic within the city centre arising from both city residents and commuters in from outside regions, but without adversely impacting on the total inflow of people to the city for business, leisure or educational purposes so as not to affect the city's economic viability.

The primary case study within the paper is Hereford, United Kingdom – an ancient Norman city within rural Herefordshire. Significant research has previously been conducted as to the transport problems within the city and such research is summarised and built on in the current paper by proposing potential solutions to the problems.

The paper concludes that sustainable travel strategies in such cities are best aligned in zones, with key strategies for the inner zones being walking and cycling and key strategies for the outer zones being "park and walk" schemes to the inner walking/cycling zones.

Keywords*: Sustainable Travel, Soft Measures, Remote Cities*

1. Introduction

Cities located within a rural area are often the primary source of employment, higher education, retail and other facilities for a wide local area, which may result in a net inflow of daily visitors due to:

- residents of the city remaining within the city for work, shopping and other needs; and
- residents of the rural area outside the city coming into the city on a daily basis for work, shopping and other needs

Should the primary means of transport be private vehicle, this may result in significant congestion within the city (which has consequent detrimental economic and social impacts) as well as other adverse environmental, social and economic impacts such as increased carbon emissions; air pollution; poor public health; and reduced incentive to invest in the area.

Therefore, careful travel planning is essential to minimise private vehicle usage without dissuading people from coming to the city, as it is important (particularly in the current economic climate) to maintain and increase the economic prosperity of the region. The focus in this paper is on sustainable travel solutions for commuters to work, as these form a significant proportion of peak time journeys.

2. Case study: Hereford, UK

2.1. Background

The main case study within the paper is the ancient cathedral city of Hereford, United Kingdom, located within the predominantly rural county of Herefordshire. Hereford has a population of

55,700 whilst the other principal towns within Herefordshire (Leominster, Ross-on-Wye, Ledbury, Bromyard and Kington) have much smaller populations, ranging from 3,200 to 11,100[1]. The nearest large city to Hereford is Worcester, which is 21 miles away, whilst the major cities of Cardiff, Birmingham and Bristol are 58, 61 and 65 miles away respectively. These geographical circumstances have led to Hereford becoming the county's centre for employment, administration, health, education facilities and shopping, resulting in significant pressure on its urban highways and its historic city centre, in which it retains an 11th Century cathedral and other historic buildings.

2.2. Geographical Factors

An additional geographical complication for Hereford city is that the River Wye divides the city between the North and the South. There is only one principal road bridge, at which the A49 crosses the river. This crossing point suffers from significant congestion which causes significant delays during peak commuter travel time[2]. There are also two further pedestrian bridges, one of which carries an important cycle route (the Great Western Way).

However, an important positive factor is Hereford's pleasant and compact city centre, with a pedestrian-only main shopping street (High Town) and numerous historic buildings, which make it a very "walkable" environment.

2.3. New Development

Hereford is currently undergoing a significant redevelopment at the Edgar Street Grid, a 40ha site to the north of the city centre, which will entail new residential, retail, office and leisure facilities. Therefore, it is important that any travel planning options take into account the impact of the new development, in terms of additional residents to the area and additional employment opportunities within the city centre. In total, Hereford plans to increase the number of households by 8,500 by 2026 (including those at the Edgar Street Grid)[2].

2.4. Journeys to Work

76% of Hereford residents work within Hereford and 65% of residents' journeys to work are less than 5km. Therefore, there appears to be significant scope for encouraging more sustainable means of travel to work, given the short distance of typical work journeys. 57% of residents take their private vehicle to work (with an additional 7% being car passengers); 18% walk to work and 8% cycle. Only 6% use public transport to travel to work, all of which consists of bus use.

The figures below[2] show that the choice of transport mode to work is strongly affected by the area of the city in which the resident lives. The majority of car journeys to work arise from the outskirts of the city whilst the majority of journeys on foot arise from within the city centre. This may indicate that a key employment zone is within the city centre:

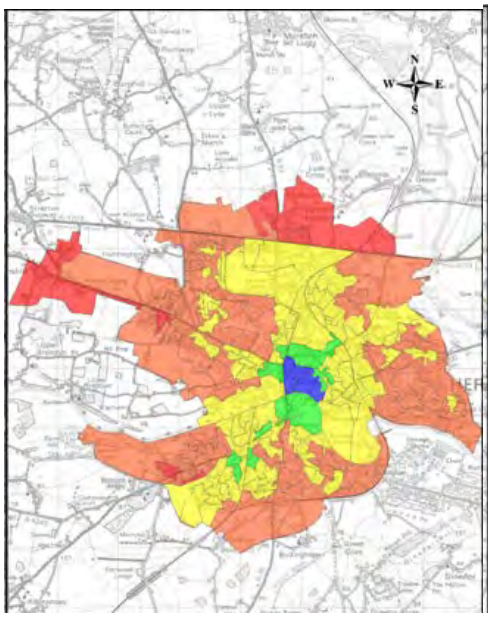


Fig 1: Car journeys to work

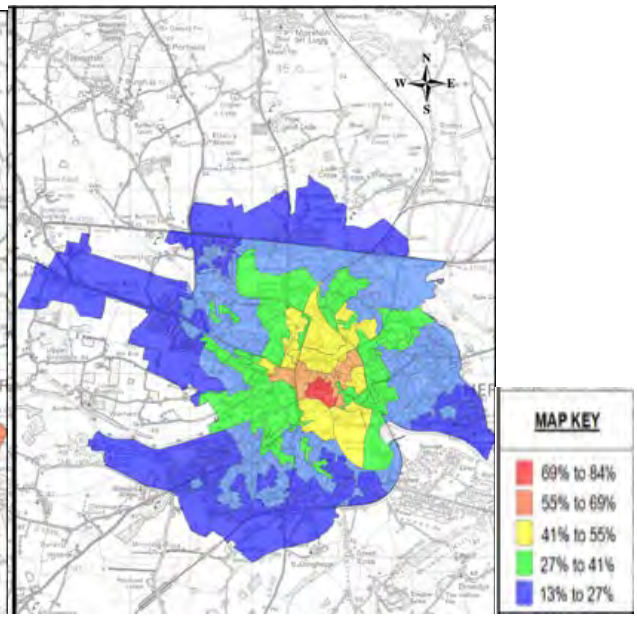


Fig 2: Journeys to work on foot

2.5. Hereford Travel Objectives

From the above background, it can be seen that the key objectives for Hereford are to:

- maintain and encourage the relatively high levels of walking and cycling to work within the city centre
- reduce private vehicle use from the city outskirts into the city centre
- protect the city's historic core against increased vehicle use
- reduce the significant congestion on the A49 crossing point over the Wye river

However, due to the current economic climate, and the reduced public sector funding now available for transport issues, low-cost approaches will be favoured to strategies which involve significant capital expenditure or long-term operation and maintenance costs.

3. Methodology

The focus of the research is on "soft measures". Such measures do not involve investment in new transport infrastructure or technologies but instead focus on changing people's behaviour so that they make better use of currently available resources. Following a review of available soft measures, a city-wide sustainable travel plan is devised to suit Hereford and other similar cities, which is set out in the Discussion.

4. Results

A summary of available soft measures[4], which can potentially be used to encourage a behavioural change in choice of transport mode, are set out below and discussed in section 5.

Table 1: Available Soft Measures

Strategy	**Details**	**Potential Financial Implications on the Local Authority**
Pedestrian-only zones	Converting the city centre to pedestrian-only zones would prevent private vehicle use in the inner zones of the city.	Cost of converting roads into pedestrian-only zones Additional car parking on the outskirts of the pedestrian-only zone
Reduced car parking	Reducing availability of city centre car parking could encourage private vehicle drivers to use different modes of transport due to the inconvenience of locating a parking space.	Reduced car parking income Additional car parking on the outskirts of the city centre
Car parking duration	Limiting city centre parking to a maximum duration (up to 3 hours) could minimise use by commuters without deterring other day visitors such as shoppers.	Reduced car parking income Additional car parking on the outskirts of the city centre
Car parking charges	Increasing city centre car parking charges could minimise use by commuters but could also deter other day visitors.	Reduced car parking income Additional car parking on the outskirts of the city centre Reduced income from day visitors, and potentially reduced business investment
Park and Ride	Car parking on the outskirts of the city centre and public transport connections into the city centre.	Additional car parking facilities and re-routing of public transport vehicles (primarily bus)
Reduced public transport costs	Local authority subsidies of public transport charges to offer reduced rates or season ticket discounts.	Cost of subsidising public transport
Public transport promotion and marketing	Greater awareness of available public transport options could increase public transport use.	Promotion/marketing cost
Walking / cycling promotion and marketing	Campaigns such as “Walk/Cycle to Work Week” can positively encourage people to switch to walking or cycling.	Promotion/marketing cost
Bicycle parking facilities	Availability of good quality and secure bicycle parking can encourage cycle use.	Cost of bicycle stands (approximately £35 to £100 per stand)
Car share schemes	Providing car share websites or other databases allows people living in the same area and travelling to the same area to share their car use.	Cost of maintaining website / databases

5. Discussion

5.1. Reduction of Private Car Use

It is self-evident that converting the city centre into a pedestrian-only zone will prevent private vehicle use within the area. However, such a measure may be unduly restrictive and unworkable for residents and outside visitors. An alternative therefore may be to enforce driving restrictions within the city centre for specific time periods, rather than a full conversion of the city centre into a pedestrian-only zone.

Parking restrictions within sustainable travel plans have been reported as effective in reducing commuter car use by an average of 24% or more, whilst the reduction in commuter car use was only 10% or more without parking restrictions[4]. From Table 1, the three strategies relating to parking restrictions (reducing car park availability, reducing parking duration, and increasing parking charges) may all be effective in reducing private vehicle use. However, only reduction of parking duration specifically targets commuter driving, whilst the other two methods impact on day visitors as well as commuters.

5.2. Sustainable Travel Alternatives

A potential sustainable alternative to private vehicle use is public transport use. It has been reported that offering public transport discounts can be highly effective in encouraging reduced car use[4]. Hereford has a railway station within its city centre but no other stations in the outskirts of the city, thus preventing commute to work by rail for Hereford residents. Therefore, the primary existing public transport option for Hereford is bus.

As mentioned above, only 6% of residents commute to work by bus, which seems a relatively low proportion. This may, potentially, be explained by the inability (due to space restrictions) to provide bus priority measures (such as exclusive bus lanes) within the historic city centre core. Therefore, bus users may be subject to the same congestion as faced by private vehicle users, but with the added inconvenience of public transport use (such as waiting at bus stops for the bus to arrive).

Given the compact nature and pleasant environment of Hereford city centre, it is therefore considered that sustainable travel options which favour walking and cycling within the city centre, rather than increasing bus use over current levels, are the optimum choices.

5.3. Hereford City Proposal

Figures 1 and 2 above show that private car use and walking are more popular respectively in different parts of the city. It is therefore useful to consider the city centre as "Zone 1" and the outer regions as "Zone 2" with different travel planning strategies for each zone.

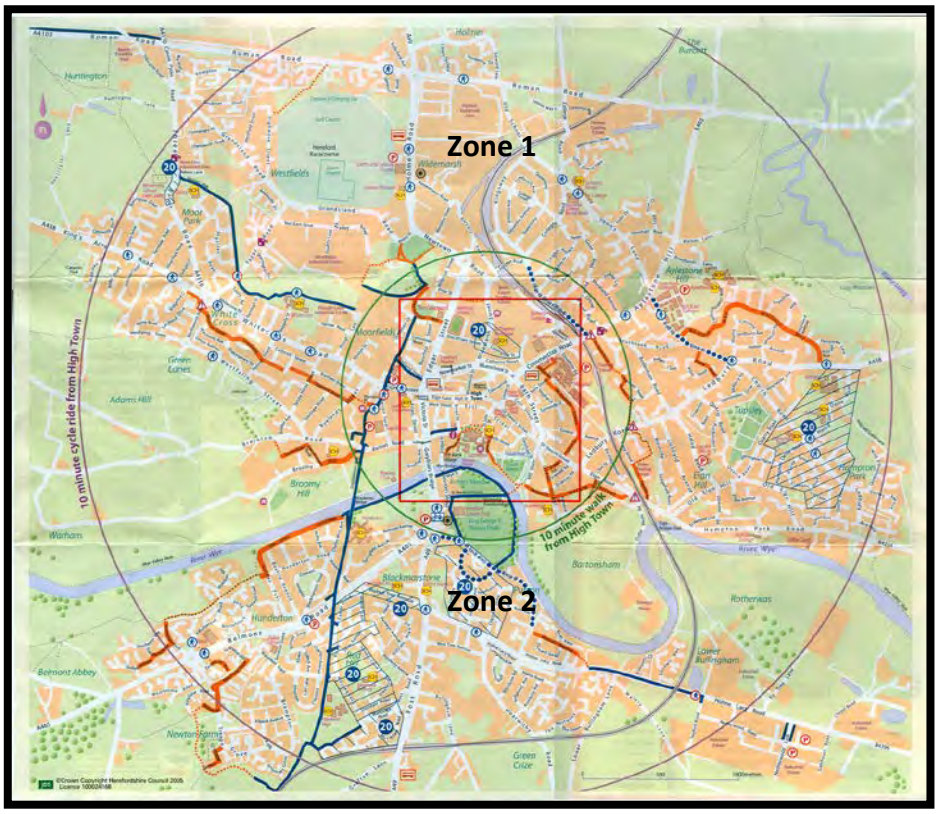


Figure 3: Map of Hereford with travel planning zones[5]

Zone 1 (circled in green - from the Wye Bridge to Hereford railway station) is 0.9 miles in length. The Herefordshire City Council mini-map[5] states the area within the red square in Zone 1 is within 10 minutes walk from High Town (the main city centre shopping street). From the above discussion, it is considered that the key approach for Zone 1 is to implement some form of parking or driving restriction within Zone 1 and couple this with measures to encourage increased walking and cycling within the Zone.

Whilst parking restrictions may <u>encourage</u> reduced private car use, driving restrictions would <u>guarantee</u> reduced private car use, and may therefore be the more effective option. However, it is not desirable to adversely impact on day visitor numbers to the city. Instead, the key target is commuters into the city for work to tackle peak time congestion. Therefore, a potential solution is to enforce driving prohibitions in the city centre only during peak commuter travel time. A proposed time frame could be, for example, 7.30am to 9.30am and 4.30pm to 6.30pm. The driving restrictions would only be within the red square in Zone 1, so as not to exceed a reasonable walking distance for most people. Naturally, there would be exceptions for disabled drivers, emergency vehicles and buses.

Enforcement of the driving restrictions could involve the placement of CCTV cameras at key road junctions within the city which would record vehicle use. Residents of Zone 1 who need to commute outside of Zone 1 during peak hours may apply for a special permit to be displayed on their vehicle to avoid receiving any penalty should they be recorded on the CCTV cameras. As it is only relatively low proportion of Hereford residents who commute outside of Hereford for work (and not all of them live within the city centre) it is considered that their vehicle use would not detract from the overall advantages of creating the peak time driving restriction zone within the city centre.

Outside of peak time hours, shoppers, tourists and other day visitors would be permitted to use their private vehicles. Whilst this may be disadvantageous from an environmental viewpoint, the potential adverse impact from an economic viewpoint of deterring such visitors may counter-balance this.

This system would therefore reduce road traffic congestion (a significant concern within Hereford); create a more pleasant walking atmosphere; and reduce carbon emissions. In order to encourage residents to accept and appreciate the change (rather than feeling that it has been imposed upon them) promotion and marketing campaigns ought to be used in the lead-up to the change, to promote the positive outcomes of the peak-time pedestrianisation.

Due to the driving restrictions to be implemented within Zone 1, drivers into the city centre from Zone 2 (as well as from outside Hereford) will need parking facilities on the outskirts of Zone 1. It is proposed that such facilities be located just before the A49 road bridge crossing the river Wye, which is currently the main congestion hotspot in the city area. This, it is anticipated, will lead to drivers from Zone 2 who wish to reach the city centre driving up to the parking facility and then walking or cycling into the city (using the pedestrian footbridges) rather than attempt to drive across the river on the A49 road bridge.

Therefore, the only drivers who will continue to use the A49 river crossing will be those who do not intend to drive into the city centre, but will instead continue past the city centre heading either to the north or south of the city.

Reducing vehicle numbers on the river crossing in this way would, it is anticipated, result in reduced congestion, so as to allow drivers who wish to bypass the city centre and reach the north or south of the city to move more easily. This would therefore alleviate the economic and social adverse impacts caused by congestion, as well as to reduce carbon emissions by the reduced private vehicle users.

Additional strategies suitable for Zone 2 include strategies to encourage cycling within the city centre. For example, efficient, smart-card operated bicycle hire facilities could be made available at the river crossing car park, to enable drivers to hire a bicycle daily to continue their commute to work once parked. At the city centre, secure bicycle parking would also need to be provided at key locations to assist such additional cyclists.

Further, the setting up and promotion of car share schemes could be valuable in encouraging reduced private vehicle use from Zone 2 (and beyond) to the river crossing facility.

6. Conclusions

Whilst it is a straightforward matter to set out a list of potential travel planning "soft measures" which may encourage sustainable transport use, a more complex issue is selecting which measures are suitable for particular circumstances. In the case of rural cities, such as Hereford, the importance of the city as a centre for a much wider local area cannot be underestimated, and so any selection of measures must take into account and balance the economic impacts, as well as the environmental and social considerations. As such, it is considered that the package of measures proposed above can be applied effectively to rural cities in the same or similar circumstances as Hereford, and can achieve the appropriate balance between environmental, economic and social aims.

The focus in this paper has been on reducing congestion and carbon emissions from private vehicle traffic caused by commuters to Hereford city centre for work. The proposals do not resolve other travel issues which may affect Hereford, primarily the concern that the A49 currently takes "through traffic" directly into the city centre. Current proposals include the development of a new bypass road to allow outside traffic passing through Hereford to bypass the city centre. However, these issues are beyond the scope of this paper.

The views expressed in this paper are mine alone, as an independent researcher, and do not represent the views of Hereford Futures Ltd or Herefordshire County Council.

References

[1] Herefordshire Council, The Population of Herefordshire, November 2009

[2] Delivering a Sustainable Transport System Stage 2 Study for the West Midlands Region, Growth Point Connectivity Stage 1, April 2010

[3] Census Data, 2001

[4] Cairns, S., Sloman, L., Newson, C., Anable, J., Kirkbride, A., Goodwin, P. (2004), Smarter Choices – Changing the Way We Travel, Department for Transport

[5]Herefordshire Council, Mini-Map, http://www.herefordshire.gov.uk/docs/Hfd_Mini_map_07.pdf

Not planning a sustainable transport system – Swedish case studies

Göran Finnveden[1,*], Jonas Åkerman[1]

[1] *KTH Royal Institute of Technology , Sweden*
** Corresponding author. Tel: +46 8 79073 18, E-mail:goran.finnveden@abe.kth.se*

Abstract: The overall objective of the Swedish transport policy is to ensure the economically efficient and sustainable provision of transport services for people and business throughout the country. More specifically the transport sector shall contribute to the achievement of environmental quality objectives where the development of the transport system plays an important role in the achievement of the objectives. The aim of this study is to analyse if current transport planning supports this policy. This is done by analyzing two recent cases: the national infrastructure plan 2010-2021 and the planning of Bypass Stockholm, a major road investment. Our results show that the plans are in conflict with several of the environmental quality objectives. Another interesting aspect of the planning processes is that the long-term climate goals are not included in the planning processes, neither as a clear goal nor as factor which will influence the future transport system. In this way the long-term sustainability aspects are not present in the planning. We conclude that the two cases do not contribute to a sustainable transport system. Thus, several changes must be made in the processes, including putting up clear targets for emissions.

Keywords: *Transport, Planning, Energy Use*

1. Introduction

One of the pillars of the Swedish environmental policy is Environmental Policy Integration, suggesting that environmental factors must be integrated into all operational areas [1]. An expression for this is the sector responsibility for environmental issues that among other things entails that a number of agencies have responsibility to follow the environmental development within their sectors.

The overall objective of the Swedish transport policy is to ensure the economically efficient and sustainable provision of transport services for people and business throughout the country. More specifically the transport sector shall contribute to the achievement of the environmental quality objective *Reduced climate impact* and to other environmental quality objectives where the development of the transport system plays an important role in the achievement of the objectives. The objective *Reduced climate impact* requires significant reductions of greenhouse gases. In Sweden, the government's target is that emissions should decrease by 40%, of which 2/3 in Sweden, by 2020 compared to 1990, and that the net emissions should be zero by 2050 [2]. These goals will require powerful economic instruments [2]. To be in line with the 2-degree target for climate change, the transport sector needs to reduce the emissions by 40 % to 2020, 80 % to 2030 and 95 % to 2050, compared to 1990 according to the Swedish Road Administration [3].

The aim of this study is to analyse if current transport planning supports the Swedish transport policy and also to what extent environmental factors are integrated into the decision making processes.

2. Methodology

Two case studies were chosen for the analysis: The national infrastructure plan 2010-2021 and the planning of Bypass Stockholm, a major road investment which is also a part of the infrastructure plan. These plans are reviewed and analysed in relation to the transport policy goals and the integration of environmental aspects in the plans. As a criterion for a sustainable

transport system we use in this paper the transport policy goal that the transport system shall contribute to a Reduced climate impact and other relevant environmental quality objectives. There are other criterion related to social and economic aspects of a sustainable transport system that could be added, but in this paper we focus on the ecological dimension.

3. Results

3.1. *Bypass Stockholm*

3.1.1. *Choice of alternatives*

The Swedish Road Administration has proposed in a statement to the Government that permission be granted for Bypass Stockholm [6]. It is interesting to study what alternatives were considered, and why Bypass Stockholm was recommended. In the Road Analysis [7], it is stated that the purpose of the road analysis is... to find the road corridor that best... ties together the north and south parts of the Stockholm County, creates a bypass for long distant traffic, improves the availability on the access roads, improves the possibilities for a common work and housing market for the region, allow a multi-nuclear region, and give possibilities for development in a region with growth. None of these goals touches on climate, environment, or sustainable development.

In the Road Analysis, three main alternatives are analysed:

- Bypass Stockholm without congestion charges
- Diagonal Ulvsunda without congestion charges. This is also a road alternative but located closer to Stockholm's inner-city than Bypass Stockholm.
- The Combination Alternative that includes congestion charges, public transport investments, and less road construction.

The Combination Alternative was developed by the Road Administration although it may not be the most competent organisation to develop that alternative since it is not responsible for public transport systems including railroads. The system for congestion charges included in the Combination Alternative is not the system that is used today. The structuring of the Combination Alternative has also met criticism [22] for having chosen expensive and inefficient investments in new tracks.

In the Road Analysis, the Combination Alternative is later rejected. The motivation is that it is not considered to meet the project goals. Here several key observations are possible. Already in the goal formulation it is set down that a road must be found. Other solutions for the foreseen transport problems are not of interest. In the Supplementary Report [6], it is stated also that “the Combination Alternative does not offer sufficient road capacity.”

The main purpose of the Road Analysis was thus, according to the above, to find a road corridor. At the same time, there are the transport policy goals to adhere to. These entail that the transport system must both be effective from a socio-economic perspective and be long-term sustainable. In the Road Analysis, there is no direct evaluation made with regard to the transport policy goals, but several aspects of these are taken up. For example, environment and climate is evaluated for the alternatives and it is concluded that the Combination Alternative is better than the Bypass Stockholm. Also related to other goals such as safety, travel times and gender aspects, the Combination alternative is preferable [8].

A number of conclusions can be drawn from this discussion:

- In the Road Analysis, the goal was to find a road corridor, not to find the best solution for Stockholm's traffic and transport problems. Thus, there is still a need to analyse alternative solutions for Stockholm's traffic problem.
- The Combination Alternative is rejected with reference to its not meeting the project goals. The choice of project goals is therefore central.
- None of the project goals in the Road Analysis is focused on environment, climate or sustainable development. If it had been so, then Bypass Stockholm could have been rejected with reference to its not meeting the project goals.
- Had the transport goals been guiding for the choice of alternatives, then Bypass Stockholm would hardly have been recommended [8].

3.1.2. *Traffic volumes*

New roads do not only lead to traffic moving from one road to another. New roads also generate new traffic [9-12]. There are several mechanisms for why new roads generate new traffic, and one can distinguish between effects in the short and long term. In the short term, new roads can lead to car-use being more attractive relative to other transport forms, and to travel itself becoming more attractive relative to alternative activities. In the long term, new roads can lead to new localisations. It can for example be attractive to develop new areas if there are better road connections, which then leads to increased traffic volumes.

The Swedish Road Administration's prognosis [6] includes short term effect on passenger vehicles. The traffic prognoses show that Bypass Stockholm leads to increased traffic volumes and decreased share of public transport. Increased traffic because of new localisation patterns is not included, however. For freight traffic, no consideration is made that new roads generate new traffic.

Thus, conclusions from this section are that:

- Bypass Stockholm leads to increased traffic volumes
- the Road Administration has likely underestimated these increases. This in turn imply that:
- congestion is underestimated
- travel times are underestimated
- accessibility is overestimated
- environment impact, including CO_2 emissions, is underestimated
- effects of development of new areas on, for example, natural environments and emissions, are not considered fully

3.1.3. *Emissions of greenhouse gases*

According to the Swedish Road Administration [6], Bypass Stockholm will increase the emissions of greenhouse gases. In our estimation this increase is underestimated. An important reason is that Bypass Stockholm likely leads to higher traffic volumes than what the Road Administration has supposed (see above). Some additional reasons are discussed below.

A failure of earlier analyses of Bypass Stockholm [7] is that these did not include emissions from the construction of the road itself [13]. This was also one of the points that the Government Offices wanted to have supplementary information on [6].

The Road Administration has in the Supplementary Report [6] analysed energy consumption and emissions from construction of the road, but unfortunately in an incomplete way. The

analysis that the Road Administration commissioned [14] includes energy consumption and greenhouse gas emissions for the road's construction, but not for the production of the materials. The construction of tunnels requires concrete and steel that are not included. An initial analysis indicates that the energy consumption for the production of these materials can be at least as large as the energy consumption that is already included in the analysis [8]. The effect on the calculations of emissions of CO_2 can thereby be significant.

In connection with analyses of environmental impacts, it is sometimes discussed how one should assess energy use and its consequences. An example relates to emissions from electricity production. The different emissions from for example hydropower, nuclear power, wind power, and coal power vary tremendously of course. Thus a discussion often arises about what electricity production should be used in the analyses, e.g. [14-16]. There are two types of data that can be chosen: average data and marginal data. Average data relate to the average electricity production during a certain time period in a certain area, for example average production in Sweden in 2008. Marginal data relate to that specific electricity production that is changed, if electricity consumption increases or decreases. Identifying the marginal electricity source may be difficult [16] and may depend on the chosen time perspective and on what decisions future politicians make. It has therefore been suggested that sensitivity analysis should be made using both low-carbon and high-carbon electricity [23].

The choice of average data or marginal data depends to a large extent on the type of analysis and question one poses, e.g. [16-19]. If the analysis is to perform an environmental accounting of a system, then the average data for the system being studied is the most suitable. If instead the analysis is for assessing impacts of changes and measures that affect energy consumption, then marginal data are the most suitable choice.

What then is relevant in this context? Environmental impact assessment focuses on analysing the consequences of a decision. If a decision entails that energy consumption changes, data for the production that changes, not the average production, should be used. That is, marginal data should be used in environmental impact assessments. CBAs also focus on analysing effects of changes. The mathematical basis for analyses is differential equations. That is, even in this case, marginal data should be used rather than average data.

However, in the analysis that Stripple makes [14], average data are used as the primary alternative. This is questionable according to the above. Instead, marginal data should be used. That is also done by Stripple in a sensitivity analysis. There he uses coal condensation power as an example of marginal electricity production. The result then becomes radically different and the emissions of carbon dioxide from construction, maintenance and operation of the road become significantly higher. With average data the emissions are 0.248 million tons CO_2 compared with 5.83 million tons when the figures for marginal electricity production are used [14].

In the Swedish Road Administration's Supplementary Report [6], a prognosis is used for future vehicles and their emissions of CO_2 [20]. In the prognosis, it is assumed that the share for renewable fuels will be circa 20% in 2020. Furthermore, it is assumed that the share of plug-in hybrids among new car sales will be 45% in 2020, and that the total share of plug-in hybrids will be about 10% that year. These assumptions are very optimistic,. The prognosis that the share of vehicles driven with renewable energy will be 20% in 2020 can be compared with the Swedish Government's target of 10% renewable fuels in transport by 2020. Furthermore, the prognosis for plug-in hybrids (circa 10% in 2020) can be compared with the

Swedish Energy Agency's prognosis of 85 000 vehicles (all-electric and plug-in hybrids together), which corresponds to circa 1.5%.

In the calculations of CO_2 emissions, two simplifications are then made that cause underestimations. One is that all vehicles that can use alternative fuels are driven exclusively with these [20]. The other simplification is that only emissions during the operation of the vehicle are considered. Excluded, therefore, are the emissions during:

- production of renewable fuel (which can be significant)
- production of electricity (which can be significant)
- production of the vehicle itself (which is larger for electric cars and plug-in hybrids than for conventional vehicles)

This leads to clear underestimations of the CO_2-emissions.

To summarise, by the Swedish Road Administration's own assessment [6], Bypass Stockholm leads to increased emissions of the greenhouse gas CO_2. This increase is underestimated, for the following reasons:

- the increase of traffic volume is likely underestimated.
- the production of materials for the roads has not been included.
- marginal data for the emissions should have been used.
- the introduction of vehicles fuelled with electricity and renewables has been overestimated.
- it has been assumed that vehicles that can use alternative fuels will be driven exclusively with these.
- emissions from the production of fuels and electricity for the operation of vehicles, have been excluded.
- emissions from the manufacturing of vehicles have been excluded.

3.1.4. *Cost-benefit analyses*

In an earlier report [13], we have discussed the use of CBAs both from a general perspective and in previous analyses of Bypass Stockholm. The reflection built on earlier CBAs [21]. In the Swedish Road Administration's Supplementary Report [6], a new CBA is made. The conclusion is reached that the CBA of Bypass Stockholm yields a positive result. There are, however, a number of deficiencies and uncertainties in the calculation. One is the underestimation of the CO_2-emissions as discussed above. Another is the zero value given to encroachment onto natural and cultural environments, some with national importance. Another important aspect is how the future developments are included. In the analysis, future powerful economic instruments that are required to reach the Reduced climate change objective are not included. It is likely that if such policy changes were included, the benefits of a new road would decrease. This is because powerful economic instruments would probably reduce traffic volumes and thus reduce benefits from time savings. In an earlier CBA [21] it was also showed that an increased oil prices would significantly reduce the benefits of a new road.

3.2 National infrastructure plan

The national infrastructure plan includes suggestions for new investments and maintenance for the Swedish transport system corresponding to approximately 50 billion euro. It was developed by the Swedish transport agencies and submitted to the government [4]. An environmental assessment of the plan was also submitted [5].

There are two overarching aspects of the Swedish transport policy, it should be economically efficient and it should support a sustainable provision of transport services. However, these two goals do not seem to have the same importance in the planning. In the plan, it is stated that the economic efficiency, measured by cost-benefit analyses, has been guiding the work [4]. The corresponding comment is not made regarding sustainable transport service. One reason for this may be the existence of established methods for evaluating the economic efficiency. For sustainability, corresponding tools are according to the plan lacking, and it is therefore difficult to evaluate [4].

The environmental assessment [5] concludes that the national infrastructure plan will

- lead to increased impacts on the biological diversity (which is relevant for the environmental quality objective A Rich Diversity of Plant and Animal Life),
- only in a limited way contribute to the achievement of the environmental quality objective Clean Air,
- not lead to a decreased number of people being affected by noise above reference values decided by the parliament and thus not contribute to a sustainable development with regards to human health and a good environment.

In relation to emissions of greenhouse gases, it is claimed that the plan will lead to small emission reductions [4, 5]. It is thus clear that the planned projects do not contribute to the significantly decreased emissions that are required. Furthermore, the agencies have underestimated the energy use and greenhouse gas emissions in several ways. They have

- not at all, or only to a limited extent, included energy use and emissions from building of infrastructure.
- assumed large fractions of vehicles which can use renewable fuels or electricity.
- assumed that all vehicles that can use renewable fuels do that all the time.
- assumed zero emissions from production of renewable fuels.
- assumed low emissions from electricity when electricity use is increasing and high emissions when electricity use is decreasing.
- only partially included the increased transport volume caused by new infrastructure.

It is therefore likely that the plan instead will lead to increased emissions of greenhouse gases.

The plan was accompanied by an environmental assessment[5] in line with European directives [24]. It is however unclear to what extent the assessment has influenced the plan since it is noted in the assessment that the suggestions in the plan is in conflict with the environmental quality objectives and thus in conflict with the transport policy.

The environmental assessment also has some limitations in relation to the requirements formulated in the directive [24]. One such requirement is that the plan should be compared with a zero-alternative that is the likely development without the plan. The zero-development (as well as the plan) includes the so called EET-strategy, a strategy until 2020 for efficient energy and transport systems developed by several Swedish agencies. In the infrastructure plan it is however concluded that it is not likely that this strategy will be implemented. Thus the zero-alternative includes a non-likely development. Furthermore, no policy measures are assumed after 2020. Although it is clear that in order to reach the Reduced climate change goal, significant policy measures are required, no such measures are assumed in the plan. Thus the transport agencies either do not believe in the goals the Parliament has decided on, or the zero-alternative does not represent the likely development. This has implications for the comparisons between the plan and the zero alternative, and also for the cost-benefit analysis

performed. Another requirement is that the environmental assessment should include also other reasonable alternatives. The proposed document did however only include an alternative with minor modifications.

4 Conclusions

The National Road Authority suggested the Bypass Stockholm in spite of this alternative being worse than other alternatives from a climate and environmental perspective and according to their own evaluation leading to increased emissions of greenhouse gases. Also the suggested infrastructure plans do not fulfill important environmental quality objectives. Since these two cases do not contribute to the fulfillment of relevant environmental quality objectives, we conclude that the two cases do not contribute to a sustainable transport system and are thus not in line with the transport policy objectives.

Another interesting aspect of the planning processes is that the long-term climate goals, or other sustainability issues, are not included in the planning processes, neither as a clear goal nor as factor which will influence the future transport system. In this way the long-term sustainability aspects are not present in the planning. Thus, several changes must be made in the processes. Examples of such changes are:

- When goals for projects and plans are formulated, environmental and sustainability aspects should be included.
- If environmental and sustainability project or policy goals are not met, new alternatives should be developed and analysed.
- Project goals should not define the solutions (as for example the goal to find a road corridor in the Bypass Stockholm case), but be open to different possibilities.
- Environmental assessments should be performed using state-of-the art methods and data.
- Long-term environmental and sustainability goals should be included in the planning as a factor that might influence the future transport system.
- Methods for assessing the sustainability of transport systems should be developed.

References

[1] Nilsson, M. and Eckerberg, K. (Eds.), Environmental Policy Integration in Practice. Shaping Institutions for Learning, Earthscan, 2007.

[2] Sweden Government Offices, En sammanhållen klimat- och energipolitik – klimat. Regeringens proposition 2008/09: 162. Regeringskansliet, 2009.

[3] Swedish Road Administration, Vägverkets handlingsplan för begränsad klimatpåverkan. Publikation 2009:82. Vägverket, 2009

[4] Swedish Road Administration, Nationell plan för transportsystemet 2010-2021. Vägverket, 2009

[5] Swedish Road Administration, Miljökonsekvensbeskrivning för Nationell plan för transportsystemet 2010-2021. Vägverket, 2009.

[6] Swedish Road Administration, Komplettering i tillåtlighetsärendet Förbifart Stockholm. Med bilagor. Vägverket, 2009.

[7] Swedish Road Administration, Nord-sydliga förbindelser i Stockholmsområdet. Vägutredning. Vägverket, 2005.

[8] Finnveden, G. och Åkerman, J., Förbifart Stockholm, klimatet och miljön – en fallstudie inom vägplaneringen. TRITA-INFRA-FMS 2009:2. KTH, 2009.

[9] The Standing Advisory Committee on Trunk Road Assessment, Trunk Roads and the Generation of Traffic. The Department of Transport. London, HMSO, 1994.

[10] Goodwin, P.B., Empirical evidence on induced traffic. A review and synthesis. Transportation, 23, 1996, 35-54.

[11] European Conference of Ministers of Transport, Infrastructure-induced mobility. OECD, 1998.

[12] Noland, R.B. and Lem, L.L., A review of the evidence for induced travel and changes in transportation and environmental policy in the US and the UK. Transportation Research Part D, 7, 2002, 1-26.

[13] Finnveden, G. and Sterner, T., Reflektioner på samhällsekonomiska analyser i allmänhet och på kalkylen för nord-sydliga förbindelser i Stockholm i synnerhet. TRITAINFRA-FMS- 2007:1. KTH, 2007.

[14] Stripple, H., Kompletterande underlag för tillåtlighetsprövning – en översiktlig miljöstudie av väginfrastrukturen i projekt Förbifart Stockholm. IVL Svenska Miljöinstitutet. 2009.

[15] Sköldberg, H. och Unger, T., Effekter av förändrad elanväning/elproduktion. Rapport 08 30. Elforsk, 2008

[16] Swedish Energy Agency, Koldioxidvärdering av energianvändning. Vad kan du göra för klimatet? Energimyndigheten, 2008.

[17] Ekvall, T., Weidema, B.P., System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. Int. J. LCA. 9, 2004, 161-171.

[18] Finnveden, G. and Moberg Å., Environmental systems analysis tools – an overview. *J Cleaner Production.* 13, 2005, 1165-1173.

[19] Tillman, A.-M., Significance of decision-making for life-cycle assessment. Environmental Impact Assessment Review, 20, 2000, 113-123.

[20] WSP, Bilparksprognos i Åtgärdsplaneringen. EET-scenario och referensscenario. Rapport 200825. WSP Analys och Strategi, 2008..

[21] Transek, Samhällsekonomiska kalkyler för Nord-sydliga förbindelse i Stockholm. Rapport 2006:18. Transek, 2006.

[22] Swedish Society for Nature Conservation, Synpunkter från Naturskyddsföreningen i Stockholm län på kompletterande underlag inför en eventuell tillåtlighetsprövning enl 17 kapitel Miljöbalken av ”Effektivare Nord-sydliga förbindelser i Stockholmsområdet”. Naturskyddsföreningen i Stockholms län, 2009.

[23] Finnveden, G, A World with CO_2-caps. Electricity production in consequential assessments. Int J LCA, 13, 2008, 365-367.

[24] European Parliament and Council of the European Union, Directive 2001/42 on the assessment of the effects of certain plans and programmes on the Environment, Brussels.

Sustainable bus transports through less detailed contracts

Helene Lidestam[1,*]

[1] *Department of Management and Engineering, Linköping, Sweden*
** Corresponding author. Tel: +46 13282433, Fax: +46 13281101, E-mail:helene.lidestam@liu.se*

Abstract: The purpose of this paper is to investigate both environmental effects and cost effects of using less specified contracts regarding bus sizes in public bus transports. The process of choosing the best bid in the public procurement of bus transports is easier if the demands of the qualifications are well specified and detailed. On the other hand, detailed contracts can force the entrepreneurs to use less environmentally friendly and uneconomical alternatives. The process of choosing the best bid in the public procurement process will be more complicated when the contracts are less detailed compared to current situations. Indeed, using less detailed contracts leads to decreased emissions and probably costs for all parts involved. A mathematical model with binary variables is developed in order to evaluate the environmental and the economic effects of using less detailed contracts in the public procurement of bus transports and in turn more suitable bus sizes. Computational results with data from a Swedish bus service provider are presented. The results of the model indicate that the emissions decrease considerably by using less detailed contracts. The results of a sub case indicate that the costs could be reduced as well, depending on how efficient the additional buses can be planned.

Keywords: *Environmental sustainability, Bus transports, Public procurement, Mathematical modeling*

1. Introduction

Many nations have converted their public transport systems from monopoly transit systems to competitive tendering. One of the first regions to use fully-tendering regime was London in 1985 [1]. An overview of international successful and less successful ways to use competitive tendering as a possibility to decrease the subsidies within the business of public bus transports has been presented [1]. The competitive tendering system has worked satisfactory in most of the European countries. Two exceptions are Italy and France where the transfer to the competitive tendering system has not affected the transports costs at all [2]. However, the costs have a tendency to be low at the first time competitive tendering is used and then instead increase for the second and third time the system is used [1]. This form of tendering often leads to changes of the structure of the actors involved in the process. Going from a market including many small actors, the actors are now few and large [1]. The system for public procurement in Sweden started through a national resolution in 1985, which led to a law coming into effect in 1989 [3]. The process for the regulations for procurement of public bus transport in Sweden is based on EU public-procurement guidelines. The most common form of contracts used in Sweden is gross contracts, where the bus entrepreneur only gets paid for the costs and is not involved in the ticket revenues. The most common way to choose the winning bid is to use so called first-price auction, which is to choose the bid with the lowest price as a winner. By using this combination the final contracts will often be very detailed. An earlier study showed that the CO_2-emissions can be reduced considerably by using less specified contracts with respect to bus sizes in the public bus transports [4]. The part of traffic being involved in the public procurement processes has increased drastically since and is now (2010) around 90%. The process of choosing the best part in the public procurement of bus transports is easier if the demands of the qualifications are well specified and detailed. On the other hand, detailed contracts will lead to limitations and could force the entrepreneurs to use uneconomical, but most of all, less environmentally friendly alternatives. The resulting contracts are indeed very detailed and there is not much inbuilt flexibility regarding for example the bus sizes. Using large buses with many bus seats for transporting few persons is

expensive, both in economic terms and most important in emission terms The trade organizations within the public bus transports area in Sweden have a common goal to double the public transports to 2020 and this ambition is in line with the aim in EU declaring that the emissions should decrease considerably. The purpose of this research was to study the cost effects of using more environmental-friendly bus traffic. The economic and environmental consequences are two of three essential aspects in sustainability. The third aspect concerns the social area. As increased emissions can lead to diseases, also this aspect is affected negatively when using non environment-friendly solutions. The outline of the paper is as follows. The methodology is presented in Section 2 and in Section 3 the mathematical model for the problem is formulated. Data from a real-life case is studied and presented in Section 4. The computational results are presented in Section 4 and finally, in Section 6, some concluding remarks are viewed.

2. Methodology

A mathematical optimization model with binary variables is developed to evaluate the environmental and cost effects of more optimized bus sizes. The mathematical model is carefully described in Section 3. We have used the program, AMPL, for modeling the problem and the commercial program CPLEX, version 10.2.0, is used to solve the model. These programs are suitable when the mathematical models include binary or integer variables. Data needed for the study is collected for one region in Sweden and is provided by a large Swedish bus entrepreneur, called Nobina Bus AB. All distances from one stopping place to the next stopping place on all chosen bus tours have been used as well as different kind of buses and their capacity in terms of number of seats. Finally, the levels of CO_2-emissions (kilogram per kilometers) and costs (Swedish crowns per kilometers) for each kinds of bus type are considered. Two opposite scenarios have been tested in order to evaluate the environmental effects of more details in contracts. The scenarios are shortly described below:

Scenario A – This is the basic scenario and it shows the current situation in the chosen region. The contract for bus traffic in the area defines which type of buses those have to be used on which bus tours.

Scenario B– The possibility to use additional buses along the lines is tested. Sometimes a large bus can drive empty from the starting place to the second last stopping place and then it can get a lot of passengers for the last part of the line. No restrictions regarding the choice of bus type. The results in this scenario show the level of CO_2-emissions when as small buses as possible, with respect to CO_2 emissions, are used. The possibility to use other bus types is also tested.

The economic effects of using more flexible and less detailed contracts in the public procurement process are evaluated in the specific case described in Section 4. This case is a sub case of the general case. In order to get a more lifelike situation, some restrictions are added into the relevant scenarios. They are further described in Subsection 4. The results from the sub case are compared to the current daily planning by the involved bus entrepreneur. The results of the model will give a solution that uses as small bus sizes as possible with respect to the costs.

3. Mathematical model

In this section we present the mathematical model for the problem of evaluation of public procurement of bus transports. The model is used in order to find as small buses as possible to use of each part of the bus tours. The model consists of an objective function, binary

variables, parameters and constraints. We first describe the parameters and the variables. Thereafter the objective function is presented and finally, the constraints are described. The original model is earlier presented [4].

Parameters

$h_i = CO_2$ emissions measured in kilogram per kilometer from bus type i.

a_{jk} = the distance from stopping place k to the next stopping place at line j.

e_{jk} = the number of people getting on the bus at stopping place k at line j.

r_{jk} = the number of people getting off the bus at stopping place k at line j.

P_i = the capacity for bus type i measured in number of seating places.

Variables

$$\boldsymbol{B_{ijk}} = \begin{cases} 1, & \text{if bus type } \boldsymbol{i} \text{ is used from stopping place } \boldsymbol{k} \text{ to the next stopping place on line } \boldsymbol{j} \\ 0, & \text{else.} \end{cases}$$

i = 1..m, j =1..n, k = 1..h

Objective function

$$\text{Min} \sum_{\boldsymbol{i}} \sum_{\boldsymbol{j}} \sum_{\boldsymbol{k}} \boldsymbol{a_{jk} h_i B_{ijk}}$$

Constraints

$$\sum_i P_i B_{ijk} \geq e_{j1} \quad \forall j, \forall k : k = 1 \quad (1)$$

$$\sum_i P_i B_{ijk} - \sum_{k=1}^{k-1} e_{jk} + \sum_{k=1}^{k} r_{jk} \geq e_{jk} \quad \forall j, \ \forall k : k \geq 2 \quad (2)$$

$$B_{ijk} \geq B_{ijk-1} \quad \forall k \geq 2, \forall i, \forall j \quad (3)$$

$$B_{ijk} \in \{0,1\} \quad (4)$$

The objective function minimizes the CO_2-emissions. The distance between all stopping places at the lines is multiplied with the CO_2-emissions from the different bus types, respectively. The constraints (1) make sure that the capacity of the used buses is enough that is that all of the people that get on the bus at the starting point have a seat place on the bus. The constraints (2) ensure that all the people getting on the buses at the forthcoming stopping places gets a seat place on the used buses. The fact that one bus has to following the whole line after it has started is described in the constraints (3). The constraints (4) express that all variables are binary, that is they could either be 1 or 0. Constraints (3) also allow buses to start on a later stopping place along the line, but it has to continue to drive to the end of the line. If there is no possibility to add buses along the line the constraints (3) can instead be described as constraints (5) given below:

$$B_{ijk} = B_{ijk-1} \quad \forall k \geq 2,\ \forall i,\ \forall j \quad (5)$$

To evaluate the specific case and to reach the lowest level of included costs, the objective function in the model is modified in the following way:

$$\text{Min} \sum_{i} \sum_{j} \sum_{k} \boldsymbol{a}_{jk} \boldsymbol{c}_{i} \boldsymbol{B}_{ijk} ,$$

where c_i = costs measured in Swedish crowns per kilometer regarding bus type *i*. The costs refer to variable driving costs. The fixed capital costs, mainly for depreciations, are added afterwards in order to compare different scenarios. The constraints used for the specific case are the same as above (1-4). The model does not consider any limitations of the number of buses that can be used for different lines. The distance between one stopping place at a line and a starting place at another line and the distance to the bus garage is not regarded in the problem. The different times for the lines are counted only as different lines so the time aspect and any possible limitations of the use of different bus types has not been considered as well in the problem.

4. Case study

Nobina AB, earlier called Concordia Nordic Bus AB, is the largest bus transport company in the Nordic countries and one of the ten largest in Europe. Nobina AB works for different public authorities in Sweden. The name of the public authority for the region considered in this study is Västtrafik. The general case included 103 different lines. The lines are divided into several sub lines depending on the number of stopping places along the line. For each line there are different variants of the line. The variants differ regarding the included stopping places and their order. Each variant of a line is used several times in a 24 hour. In total it is 2 044 tours including 2 037 stopping places during a day in the selected area and the number of counted people getting on (and off) the buses is 34 312. Seven types of buses are used by Västtrafik and taken into account in the scenarios. The capacity of the different type of buses is from 23 seats to 56 seats and the levels of CO_2-emissions range from 0,83 kg/km to 0,99 kg/km. For each bus type, the related seat capacity and CO_2-emissions are given. The CO_2-emissions are defined by kilogram per kilometer. The presented model will minimize the level of CO_2-emissions.

The calculations of the emissions are based on road driving with few stops. The most important factor to consider in this paper is the difference in emissions due to the size of the bus type, which in this case is measured in number of seats in each bus type. Therefore the other depending factors, for example type of engine and driving properties are equal in of all the bus types. The considered engine in all of the bus type is a euro3 engine. The newer engine euro5 has fewer emissions but the difference is mostly related to the NOx-emissions and SOx. The figures on CO_2-emissions are considered proportionate to fuel-consumption. The fact that a full bus has more CO_2-emissions compared to an empty bus has not been considered in the optimization, however, it can be calculated and evaluated after the optimization has been made if needed. In scenario B, two additional bus types are possible to use; one large bus taking 65 passengers with 1,15 kg/km of CO_2-emissions and one small bus taking only eight passengers with 0,3 kg/km of CO_2-emissions.

An area of bus traffic is chosen from the general case in order to investigate the economic effects on a given real planning situation. One hundred tours (around 5 %) of 2 044 in total

are included in the specific case. The total length of these tours is 5 750 kilometers to compare to the total length of the general case which is 44 790 kilometers. The bus traffic for the specific case is chosen in cooperation with the planning manager at the involved company Nobina AB. One reason for choosing this area and these tours was that the traffic is expected to be heavy and the buses are supposed to be more full compared to an average tour in the area of the general case. The 100 used tours are divided into 14 bus trips. The bus trips describe the day of each bus. The current situation at the chosen region is that 14 large buses (Express buses) are used on the 100 tours. The bus goes from the garage in the morning and back to the garage at the evening. The bus trips can include from five to nine different tours. A typical example of a bus trip is illustrated in Figure 4.1. This bus trip (on the x-axis) includes seven different bus tours (the piles) represented in time order, that is the first tour represents the early morning and the last tour represents the late afternoon or evening for the bus trip. The y-axis shows the number of passengers on each tour. Each bus tour includes a number of lines between the stopping places and the number of passengers in Figure 4.1 refers to the highest number of passengers on the each tour. That means that the situation can be that the bus drives empty most of the distances and drives with many passengers, for example 50, only on one of the included lines. Then the number of passengers, in Figure 4.1 below, will be 50 on that tour. Most of the bus trips look like the one below in that sense that number of passengers on the tours included varies a lot. As mentioned before only type of large buses are used today in this area. The average number of the highest level of passengers is 24 on the 100 included tours.

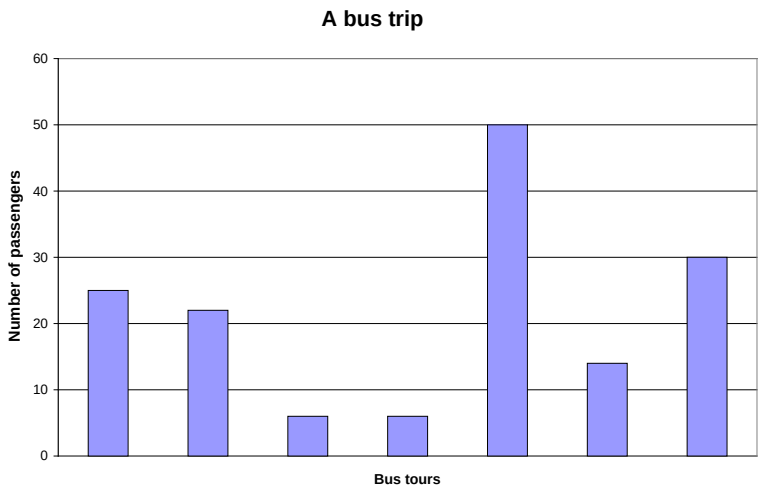


Figure 4.1 Example of a bus trip

Alternatives to use only large Express-buses can be to use as small buses as possible on the fourteen tours. That is further on called using adaptive bus sizes and that will of course also lead to the use of fourteen buses. Another alternative that will be investigated on the specific case is to use another bus type, here called Middle-bus, as a standard bus and then use smaller buses, here called Mini-buses, as additional buses that can be used whenever needed between one or several stopping places. The capacity of the Middle-bus, in terms of seats, is 32 and the capacity of the Mini-bus is 15. The CO_2-emissions from the Middle-bus and the Mini-bus are 0,45 and 0,35 kilogram per kilometers, respectively, compared to the level of 0,96 kilogram per kilometers from the Express-bus. Regarding the alternative of using adaptive bus sizes, the bus type Ordinary is also taken into account. The level of CO_2-emissions from that bus type is 0,93 kilogram per kilometers and the number of seats is 46. The considered variable costs are referred to costs for operating the bus and costs regarding the bus driver. The

included fixed costs are capital costs, mainly with respect to the depreciations and based on the purchase cost. The levels of the different costs are collected and evaluated by the planning manager for Nobina AB in the area of the specific case.

5. Results

The resulted levels of CO_2-emissions from the scenarios in the general and the specific case are presented in Table 5.1. The level of CO_2-emissions is calculated based on the level of emissions per 24 hours workday. The bus traffic on workdays is on average four times more intense compared to the bus traffic on Saturdays and Sundays. We have estimated the number of workdays in a year to 245 and the official holidays, including Saturdays and bridges days, to 120. The differences compared to Scenario A are given in percent.

Table 5.1 Comparison of the two cases.

Case	Scenario	CO_2 kg/year	Difference
General	A	11 765 150	0 %
General	B	7 653 800	- 34 %
Specific	A	1 554 300	0 %
Specific	B	1 183 050	- 24 %

The results from the two scenarios, indicate a clear relation between CO_2-emissions and contract-flexibility. By letting the number of passengers decide which bus size to use instead of following the contract regulations, the CO_2-emissions can be decreased by 34 %. The possibility to add buses along the tours create a need for more small buses. A disadvantage by using smaller buses is the fact that more buses have to be used. The buses will in total be used on shorter distances but indeed more buses on a line results of course in more bus drivers. It is a trade-off between the fixed costs of having several bus drivers and the ambition to drive as small buses as possible in order to reduce the CO_2-emissions. The fact that the difference between Scenario A and Scenario B in the general case is larger compared to the difference between the same scenarios in the specific case indicates that the chosen area for the specific case is not fully representative for the general case. The results above also tell that there are other areas in the general case that would gain more, with respect to lower CO_2-emissions, by using more flexible and less regulated contracts. The solution times regarding the general case are less than 20 minutes and the solution times for the specific case are all very small, below one minute.

The current situation, only use Express-buses, is compared to other alternatives regarding the specific case. The first alternative to investigate was to adaptive bus sizes. To find and use the smallest bus for each trip resulted in seven Express-buses, six Ordinary-buses and one Middle-bus and these changes would lead to 5 % lower CO_2-emissions on the same number of active kilometers compare to the current situation. The second alternative investigated was to use another type of base bus, Middle-bus on all trips and then when necessary use additional, Mini-buses, on parts of the tours. By using fourteen Middle-buses and seventeen Mini-buses the CO_2-emissions can be reduced by as much as 47 %.

The results, however, only present the CO_2-emissions from the active driving in the tours. The driving from the bus garage to the first tour in the morning and the driving from the last tour in the evening back to the bus garage are not taken into account. Also the fact that the buses used on one or several sub distances between stopping places on one tour also are used for other sub distances on other tours lead to additional CO_2-emissions. These extra CO_2-

emissions are not been taken into consideration in the above table. The circumstances of using additional buses on the trips lead to a larger number of active kilometers, 6 677 compared to 5 750. The plan of where different buses will be used has been showed to the planning manager. He has, from his point of view, estimated the practical need for buses in the current area to be 10 additional Mini-buses. Therefore the calculations regarding costs are made for using 10 additional buses. The results measured in emissions and costs for using different kind of combinations of bus types on the fourteen bus trips are presented in Table 5.2.

Table 5.2 The results regarding CO_2-emissions and costs from the specific case.

Used buses	Active kilometers	CO_2 kg/year	Difference	Total costs (SEK/year)	Difference
14 Express	5 750	1 518 000	0 %	30 449 000	0 %
7 Express 6 Ordinary 1 Middle	5 750	1 438 000	- 5 %	28 009 000	- 8 %
14 Middle 10 Mini	6 677	800 786	- 47%	24 997 660	- 18 %

The calculations made by the planning manager showed that adding 10 more buses in the current situation will increase the costs by 10 %. There is apparently a gap from decreasing the costs by 18 % to increasing the costs by 10 % due to how the additional buses can be scheduled. However, the value of lowering the emissions and in turn improving the environment is hard to measure and compare to the increasing related costs.

6. Conclusions

The results of the mathematical model indicate that all parts involved in the public procurement process, the public authority, the entrepreneur and the customers, will gain from more flexible and less detailed contracts. The results from the general case expose notable lower levels of CO_2-emissions when the contracts are more flexible and without detailed restrictions. The levels of CO_2-emissions decrease by 34 % from the current situation to the most flexible scenario (Scenario B). The results from the specific case indicate that the costs could be reduced as well, depending on how efficient the additional smaller buses can be planned. The results indicate that the emissions can be reduced up to 47 % by using smaller buses in traffic and the costs can in worst case increase by 10 %. Anyway, there are possibilities to decrease the costs as well if the operations planning changes. That could be done for example by expanding the planning area for the buses in order to increase the possibility to make use of returns to scale and coordination advantages. Other kinds of entrepreneurs, such as taxicabs, could also be used in addition to the ordinary buses. That will lead to more flexibility. Another base for getting lower cost could be to plan the bus trips in a different way. The occupancy level on the buses in general could probably be higher if the tours for a bus trip have more equal occupancy levels. The number of on and off-going people in the studied bus trips in the specific case varies a lot along the trip. The possibility to use parking places for the buses along the tours in addition to the bus garage could also decrease the bus driving. Directions for future research could therefore include the above suggestions in order to show the possibility to reduce both the CO_2-emissions as well as the costs considerably. In order to get a more complete view, other aspects, for example the traveler behavior connected to the level of occupied buses should be further investigated. The results from the optimization model show that detailed rules in the public procurement process lead to increased CO_2-emissions and probably higher overall costs, and therefore it would be

highly motivated by the politicians to evaluate the Swedish system. The research will therefore contribute to the operation management planning in order to achieve the overall aim to reduce CO_2-emissions. The actors in the public bus transport business should as well be interested in getting insight in how fewer restrictions in the contracts will affect them.

References

[1] D.A. Hensher and I.P. Wallis, Competition tendering as a contracting mechanism for subsidising transport – The bus experience, Journal of Transport Econimics and Policy 39, 2005, pp. 295-321.

[2] A. Boitan and C. Cambini, To bid or not to bid, this is the question: the Italien experience in competitive tendering for local bus services, European Transport 33, 2006, pp. 41- 53.

[3] P. Elvingson, Bättre kollektivtrafik, ISBN 91 558 6951 3, Svenska Naturskyddsföreningen, 2005. (in Swedish)

[4] H. Lidestam and M. Abrahamsson, Mathematical modeling for evaluation of public procurement for bus transports in terms of emissions, Management of Environmental Quality 5(3), 2010, pp. 645-658.

Analysis of alternative policy instruments to promote electric vehicles in Austria

Viktoria Gass[1,*], Johannes Schmidt[1], Erwin Schmid[1]

[1] *Department of Economics and Social Sciences, University of Natural Resources and Life Sciences, Feistmantelstrasse 4, A-1180 Vienna, Austria*
[*] *Corresponding author, Tel: +43 147654 3594, Fax: +43 1476543692, E-mail: v.gass@students.boku.ac.at*

Abstract: The large amount of CO_2 emissions and of fossil fuel consumption by the transportation sector makes the sector central for attaining the EU energy and climate policy targets. Consequently, new propulsion systems are developed in the automotive industry, which currently have cost disadvantages compared to conventional internal combustion engines (ICE). The article provides a review on support measures for electric vehicles which have been currently implemented within the European Union. In a case study analysis for Austria, we analyze different policy instruments including a CO_2 tax aiming to support the introduction of electric vehicles in Austria. We have calculated and compared total costs of ownership (TCO), which includes all costs associated with the ownership of an automobile including costs of purchasing, operating and maintaining, charges and taxes as well as costs of recycling and disposal. A survey on main specifications of electric vehicles has been conducted among the main automobile manufacturers and importers in Austria. Based on this survey, TCO have been calculated dynamically from 2011 to 2020 for a business as usual (BAU) scenario considering currently implemented taxes and subsidies for ICE and electric vehicle systems. Three alternative policy support measures have been assessed to promote EV to ICE until 2015. We conclude that an up-front price support seems to be favorable over taxation systems. The paper focuses only of the effectiveness of the three policy support measures but does not analyze their efficiency.

Keywords: *Electric vehicles, Total cost of ownership (TCO), Fiscal policy instruments, Break-even*

1. Introduction

Currently, 98% of the transportation sector in the EU depends on fossil fuels. The sector is responsible for approx. 21% of the greenhouse gas (GHG) emissions, with more than half of the emissions produced by passenger cars [1]. The EU Directive (2009/33/EC) on the promotion of clean and energy efficient road transport vehicles has been released to foster a broad market penetration of environmentally-friendly vehicles in order to decarbonize the transportation sector and to reduce oil dependency.

Several new propulsion systems as plug-in hybrids, range extenders as well as electric vehicles have emerged and entered the market or are ready to enter the market in the near future [2]. However, in order to achieve a shift in the transportation sector the cost disadvantages of the newly emerged propulsion systems have to be overcome. Economic viability and a successful introduction of alternative propulsion systems will mainly depend on economic aspects such as relative costs. The gap between the total cost of ownership (TCO) of alternative transportation systems and ICE should be temporarily closed by appropriate policy interventions to promote environmentally-friendly vehicles.

Current research regarding the economic viability of electric vehicles (EV) focused mainly on lifecycle cost analysis [3,4,5]. Thiel et al. [3] compared the well-to-wheel CO_2 emissions, costs and CO_2 abatement costs of passenger light duty vehicles including gasoline vehicles, diesel vehicles, diesel hybrid vehicles, plug-in hybrid and battery electric vehicles [3]. A static comparison has been conducted for the years 2010, 2020 and 2030 under a new energy policy scenario for Europe. They conclude that electric vehicles can clearly contribute to a decarbonization of the transportation system if renewable electricity is used. According to [3],

current cost disadvantages of electric vehicles can be overcome by adequate policy support instruments to attain payback periods of less than five years.

Ogden et al. [4] conducted an analysis of the societal lifecycle cost of transportation including the purchase price, fuel costs, externality costs of securing oil supply and damage costs for emissions of air pollutants and greenhouse gases which are calculated over the full fuel cycle. Thomas [5] developed a dynamic computer simulation model that compares the societal benefits of replacing conventional gasoline cars with vehicles that are partially electrified, including hybrid electric vehicles. He concludes that electric vehicles in combination with hybrids, plug-in hybrids and biofuels will be necessary to achieve an 80% reduction in greenhouse gas emissions below 1990 levels by simultaneously cutting dependence on imported oil and eliminating nearly all controllable urban air pollution from the light duty vehicle fleet. However, to increase market shares, market barriers have to be overcome. Therefore, the consumer perspective and thus effective and efficient policy instruments should be the focus of further research. Taxation systems regarding vehicles vary strongly between countries.

The aim of the article is to analyze different policy instruments by comparing total cost of ownership (TCO) of EV and ICE in Austria. TCO are calculated dynamically from 2011 to 2020 for a business as usual (BAU) scenario considering currently implemented taxes and subsidies for ICE and EV in Austria. In contrast to lifecycle cost analysis of alternative propulsion systems, our analysis focuses mainly on the total cost of ownership and places the consumer perspective in the center of the analysis. The consumer perspective is placed in the center of our analysis as only early adopters are willing to accept the current cost differential between ICE and EV. As such instruments necessary to close the gap are considered to be necessary in order to achieve a mass market introduction.

The article is structured as follows. Section 2 provides an overview of the support schemes currently launched in the EU-15. Section 3 presents the methodology and data. An analysis on different policy support instruments to equalize the TCO of EV and ICE in Austria is shown in Section 4 and section 5 presents major conclusions from our analysis.

2. Implemented support schemes for EV in the EU-15

Many EU member states have introduced national targets for the EV driving stock, the expansion of charging infrastructure, or production targets of electric vehicles [6]. Most EU member states overcome the cost disadvantage of alternative vehicles by introducing policy instruments such as an up-front price support in order to increase the affordability of electric vehicles by reducing the marginal capital cost, which is considered as one of the key barriers for consumers [7]. Within the EU-15, passenger cars have mainly been the target of a tax reform that takes into account the CO_2 emissions of vehicles. Policy instruments that are currently implemented in order to stimulate the up-take of alternative propulsion systems consist of [7]:

- *Registration or purchase taxes*
  Registration or purchase taxes are an up-front cost and can have a strong impact on CO_2 emissions and the market, if costs are differentiated with regard to the specific CO_2 emissions of the vehicles. In France, a bonus/malus system has been introduced whereby vehicles above certain CO_2 emission thresholds have to pay a malus and vehicles under the threshold receive a bonus. Such a system may increase the political acceptability as well as of consumers, because it can be designed in a revenue neutral manner [7].

- *Circulation or motor taxes*
  Circulation or motor taxes have according to [7] a limited effect on the purchase decision as they are annual or monthly charges. Although they are considered to be politically acceptable, their impact to promote EV is rather low as the cost range of such measures is limited.
- *Fuel taxes*
  Fuel charges have limited short-term effects, because they do not change the purchasing decision of consumers in the longer term [8]. Furthermore, they are considered to be politically prohibitive.

Policy instruments to stimulate the up-take of alternative propulsion systems are subsidies, taxation of benefits in kind and treatment of depreciation (relevant for company cars) and in use and parking charges [8]. Table 1 provides an overview of the currently implemented support measures [7-10].

Table 1: Policy instruments to supporting EV in the EU-15

Country	**Economic instruments for the support of EV**
Austria	Exemption from fuel consumption tax Exemption from monthly vehicle tax
Belgium	Purchasers of electric cars receive a personal income tax reduction of 30% of the purchase price (with a maximum of EUR 9,000)
Finland	Exemption of fuel tax
Italy	A tax incentive of EUR800 and a two year exemption from annual circulation tax is granted for the purchase of a new passenger.
Denmark	Exemption from registration tax and annual circulation tax. Further EV qualify for free parking
Germany	EV exempt from the annual road tax for a period of five years from the date of the first registration
Spain	Various regional governments grant tax incentives for the purchase of alternative fuel vehicles including EV – approx. EUR 6,000
France	Bonus-Malus System; New Cars with CO2 emissions below 125 g/km receive a premium. EV receive currently EUR 5,000
Greece	EV exempt from registration tax. If engine capacity below 1929 cc, exemption from road tax. Further EV are even allowed to drive in Athens when parts of the city are restricted to ICE to reduce traffic congestion.
Ireland	EV exempt from registration tax – approx. EUR 2,500.
The Netherlands	approx. EUR 6,400 reduction from the registration tax
Portugal	Exemption from registration tax
Sweden	Exemption from annual road tax for a period of 5 years upon first registration
United Kingdom	Exemption from annual road tax
Ireland	Exemption from registration tax
Luxemburg	Annual circulation taxes based on CO_2 emissions

3. Data and Methodology

Total cost of ownership (TCO) includes all costs arising with the ownership of an automobile including costs of purchasing, operating and maintaining, charges and taxes as well as costs of recycling and disposal over a specified timeframe under consideration of opportunity costs. TCO is defined as following:

$$TCO = -I + \sum_{t=1}^{N} c\,(1+r)^{-t} + R\,(1+r)^{-N} \quad , \qquad (1)$$

where *I* represents the purchase price, *c* maintenance and operating costs, *r* the discount factor and *R* the resale price. Maintenance and operating costs include infrastructure charges, insurance, fuel consumption tax (NoVA) and the monthly engine related vehicle tax (motorbezogene Versicherungssteuer).

TCO have been calculated for limited vehicle options based on a survey conducted with the main automobile manufacturers and importers in Austria. The survey includes data on technical specifications and costs. The EVs included in the analysis are either already available for sale or will be in the near future. The survey has been conducted with the automotive offices of Nissan, Peugot, Renault, Mitsubishi and Think City in Austria. The ICE have been chosen of similar size and technical specifications, which are the most often sold cars in the vehicle class [11]. Technology and performance assumptions for ICE have been derived from the respective automobile manufacturers [12,13]. Table 2 provides an overview of the main specifications as well as the main resulting performance and cost figures of EV and ICE for which the TCO have been calculated dynamically over the period 2011 until 2020.

Table 2: Technical, performance and cost assumptions of analyzed vehicles

	VW Golf Rabbit	**VW Golf Rabbit**	**Nissan Leaf**	**Peugeot iOn**	**Mitsubishi i-Miev**
Technology					
ICE engine displacement (l)	1.6	1.2	-	-	-
Turbocharger (yes/no)	yes	yes	-	-	-
PT power (kW)	77	77	-	-	-
Electric motor power (kW)	-	-	80	47	49
Battery capacity (kWh)	-	-	24	16	16
Energy source	Diesel	Gasoline	Electricity	Electricity	Electricity
Performance					
Weight (kg)	1,314	1,314	1,545	1,120	1080
Acceleration 0-100 km/h (in s)	11.3	10.6	-	-	-
Top speed (km/h)	190	190	140	130	130
Fuel consumption (l/100km)	4.1	5.2	-	-	-
Electricity consumption (kWh/100km)	-	0	15	15	15
Tailpipe CO_2 emissions (g/km)	107	121	-	-	-
Costs					
Vehicle incl. VAT and NoVA (EUR)	20,350	22,120	39,600	36,000	35,900
NoVA (fuel consumption tax in % of purchase price)	4%	4%	0%	0%	0%
Battery cost (EUR/kWh)	-	-	600	600	600
Battery cost (EUR)	-	-	14,400	9,600	9,600
Loss in value p.a.	17%	16%	32%	32%	32%
Maintenance cost (EUR/100km)	4.6	4.1	2.5	2.5	2.5

The TCO have been calculated over a period of five years assuming that 15,000 km are traveled annually. According to the survey, automobile manufacturers expect that the battery of EV needs to be replaced after approx. 75,000 km. We assume that vehicles are sold after

five years, because no estimates on battery replacement costs are currently available. Both assumptions refer to results of [13] and have been confirmed by the survey. The percentage loss in value p.a. as well as maintenance costs are guesstimates of manufacturers received in the survey. Average figures are applied to all EV, because the guesstimates from the respective manufacturers differ slightly and empirical values are not available yet. We also assume that the purchase price of ICE will not change over time, because further efficiency gains in ICE are costly [2]. Furthermore, learning effects from increased production volumes decrease the purchase price. The learning effects have been depicted from an analysis conducted by [15] and are consistent with [3,14,16]. Currently, battery costs amount to approx. 600 EUR/kWh and shall decrease to approx. 300 EUR/kWh by 2015 if the projected production volumes are reached. Projected productions volumes are reflected in the assumed learning rate and have not been separately been calculated. As such price reductions resulting from an increase in production volume are already reflected in the calculation of the TCO.

The current gasoline price in Austria amounts to 1.3 EUR/l and for diesel to 1.1 EUR/l including taxes and charges. The gasoline and diesel prices are assumed to be consistent with the projected oil prices in the Annual Energy Outlook. The electricity price for Austrian households amounts currently to 0.15 EUR/kWh including taxes and charges. The average increase in the electricity price (EEX Phelix baseload) from 2000 until now has been approx. 2.8% p.a. Similar price developments are assumed to 2020.

4. Results

The three policy scenarios consist of an up-front price support, a CO_2-tax as well as a fuel consumption tax for ICE, respectively. The level of incentive to make EV competitive from 2011 onwards is shown for each policy instrument.

In a BAU-scenario, the EV becomes cost-competitive with ICE in the year 2015. TCO of ICE are increasing over time mainly due to rising fuel costs. The decrease in TCO of EV is mainly attributed to the projected decreases in battery costs. The TCO time line for EV and ICE is shown in Fig. 1.

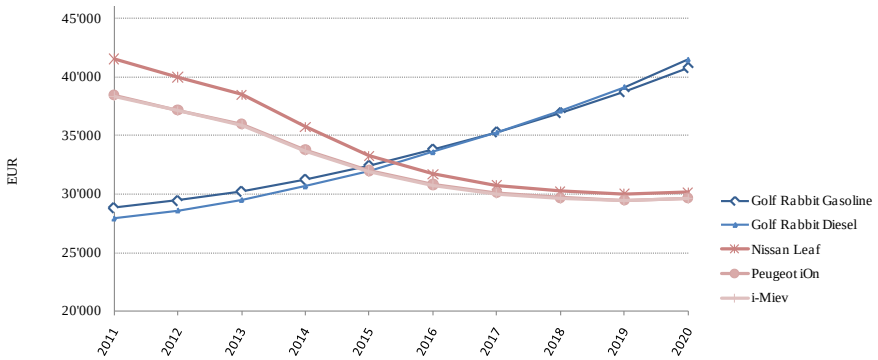


Fig. 1: TCO – BAU-scenario

The BAU scenario implies that TCO of ICE and EV will converge in 2015. However, it only may convergence if the projected volumes are produced to realize the necessary economies of scales. Consequently, subsidies may be necessary to realize the projected production volumes. As shown in Section 2, many countries have currently implemented or are considering to implement an up-front price support (e.g. usually in the form of an exemption of the registration tax) for alternative propulsion systems. An up-front price support is considered as an effective policy instrument, because consumers put much larger emphasis on the purchase

price of a vehicle than on the resulting maintenance and operating costs [8]. However, by introducing an up-front price support for EV, the question arises of how much price support is necessary to incentivize sufficient uptake of EV.

In our analysis, we have calculated alternative levels of upfront price support to offset the gap between ICE and EV TCO (table 3). It is assumed that covering the entire price differential would require large amounts of subsidies despite remaining technical limitations such as limited range that may lead to higher costs [8]. However, a regressive price support system would minimize windfall profits. Nevertheless, the interviewed representatives of automotive manufacturers clearly stated that final purchase prices are set under consideration of governmental support and that EV will be available for sale only in countries with governmental support measures at a level that is considered sufficient from the perspective of car manufacturers. The level of price support should be adjusted annually to account for learning effects. High political and public acceptability is attributed to an up-front price, however some moral hazard problem will remain [7].

Table 3: Levels of up-front price support until 2015 in Euro

	2011	2012	2013	2014	2015
up-front price support	10'000	8'000	5'500	3'000	0

In a second scenario, we have analyzed the level of a CO_2 tax for the transportation sector in order to promote EV. A CO_2-tax is generally considered to be an effective policy instrument from an environmental point of view, because it contributes to lowering CO_2 emissions. Furthermore, it is a cost-effective policy instrument as it generates revenues for the government that can be used to subsidize cleaner technologies [18]. Besides reducing greenhouse gas emissions, a CO_2-tax has the capacity to reduce other external costs of ICE such as changing driving habits, reducing traffic congestions and other emissions e.g. fine dust [18].

A CO_2 tax can be levied by directly taxing gasoline and diesel corresponding to the carbon content of the respective fuel. This implies that a CO_2 tax would result in an increase in the respective fuel price. The level of CO_2 price necessary to sufficiently promote EV is shown in Table 4 and Table 5 shows the resulting gasoline and diesel prices.

In our analysis, the implementation of a CO_2 tax becomes effective, if the CO_2 price is approx. 2’000 EUR/t. Currently, the CO_2 price on the EU Emission Allowances spot market trades at 15 EUR/t. Increasing the CO_2 tax to up to 2’000 EUR/t is seen as politically infeasible. Therefore, the introduction of a CO_2 tax as sole policy instrument to reduce the price differential and to achieve a certain market penetration of EV is not considered viable.

Table 4: Required levels of CO_2 tax until 2015 in EUR/t

	2011	2012	2013	2014	2015
CO_2 tax	2'500	2'300	2'250	1'000	0

Table 5: Resulting gasoline and diesel prices until 2015

	2011	2012	2013	2014	2015
Golf Rabbit Gasoline					
CO_2 emission g/km	121	121	121	121	121
Fuel consumption l/ km	0.052	0.052	0.052	0.052	0.052
CO_2 emission g/l	2'327	2'327	2'327	2'327	2'327
CO_2 tax ct/g	0.250	0.230	0.225	0.100	0.050
ct/l	581.7	535.2	523.6	232.7	116.3
Golf Rabbit Diesel					
CO_2 emission g/km	107	107	107	107	107
Fuel consumption l/ km	0.041	0.041	0.041	0.041	0.041
CO_2 emission g/l	2'610	2'610	2'610	2'610	2'610
CO_2 tax ct/g	0.250	0.230	0.225	0.100	0.050
ct/l	652.4	600.2	587.2	261.0	130.5

The necessary levels of the fuel consumption tax (NoVA) have been analyzed as third policy option. Currently the NoVA amounts to 4% of the purchase price for the cases under consideration. As shown in Table 6, the NoVA would need to be increased by up to 45% in order to sufficiently support EVs from 2011 onwards. Similarly to the CO_2-tax, an increase in the NoVA as sole policy instrument is considered to be politically infeasible and it may cause adverse effects on the total automotive market.

Table 6: Required level of NoVA in %

	2011	2012	2013	2014	2015
NoVA	45	40	35	30	0

5. Concluding Remarks

Several TCO have been calculated for EV and ICE. The BAU-scenario shows that EV shall be competitive with ICE in the year 2015 if no additional policy actions are taken. However, significant learning effects are assumed to decrease costs of electric cars. Such learning effects can be mainly triggered if policy makers sufficiently support research and development of new environmentally friendly vehicle technologies. The analysis shows that both CO2 and NoVA taxes, which increase the costs of ICE, have to be prohibitive to make electric cars competitive. Introducing such levels of taxes seems not politically feasible besides other adverse effects on the vehicle market. Therefore, up-front price support systems (e.g. direct financial support, exemption from registration tax, bonus/malus system, etc.) seem to be favorable over the taxation systems. These results are confirmed by literature. Even though cost disadvantages can be overcome by policy support instruments, technical limitations of EV such as limited range and relatively long charging times remain. In addition to closing the TCO gap between EV and ICE and to overcoming technical limitations, policy makers shall focus on providing infrastructures for a large-scale take-up of EV.

References

[1] EU Insight, Driving toward a more sustainable future, Issue No. 29, 2009.

[2] S. Schmid, P. Mock, H. Friedrich, Welche Antriebstechnologien prägen die Mobilität in 25 Jahren, Zeitschrift für Energie Markt Wettbewerb, 4, 2010, pp.6-11.

[3] C. Thiel, A. Perujo, A. Mercier, Cost and CO_2 aspects of future vehicle options in Europe under new energy policy scenarios, Energy Policy, 2010, pp. 7142-7151.

[4] J. Ogden, R. Williams, E. Larson, Societal lifecycle costs of cars with alternative fuels/engines, Energy Policy, 2004, pp. 7-27.

[5] C.E. Thomas, Fuel cell and battery electric vehicles compared, International Journal of Hydrogen Energy, 2009, pp. 6005-6020.

[6] F. Kley, M. Wietschel, D. Dallinger, Evaluation of European electric vehicle support schemes, Working Paper Sustainability and Innovation No. S 7/2010, Frauenhofer ISI, 2010.

[7] AEA Energy & Environment, Hybrid Electric and Battery Electric Vehicles: Measures to Stimulate Uptake, Version 2, 2008.

[8] AEA, Market Outlook to 2022 for Battery Electric and Plug-in Hybrid Electric Cars, Issue 1, 2009.

[9] European Automobile Manufacturers' Association (ACEA), Overview of Tax Incentives for Electric Vehicles in the EU, 2010.

[10] Joint Research Center, Well-To-Wheels analysis of future automotive fuels and powertrains in the European context, Version 3, 2008.

[11] OEAMTC, Zukünftige Elektrofahrzeuge, 2010.

[12] VW, Der Golf – Preise, Austattungen, Technische Daten, November 2010.

[13] K. Handa, H. Yoshida, Development of Next Generation Vehicle „i-MiEV", Mitsubishi Motors Technical Review, No.19, 2007.

[14] The Boston Consulting Group, The Comeback of the Electric Car? How Real, How Soon, and What Must Happen Next, 2009.

[15] PricewaterhouseCoopers, Elektromobilität in Österreich, internal paper, 2010.

[16] McKinsey, Roads toward low-carbon energy future: Reducing CO2 emissions from passanger vehicles in the global road transportation system, 2009.

[17] Element Energy, Strategies for the uptake of electric vehicles and associated infrastructure implications, 2009.

[18] H. Hammer, S. Jagers, What is a fair CO_2 tax increase? On fair emission reductions in the transport sector, Ecological Economics, 2007, pp. 377-387.

Comparative Analysis of Performance and Combustion of Koroch Seed Oil and Jatropha Methyl Ester blends in a Diesel Engine

Tapan K. Gogoi[1,*], Shovana Talukdar[1], Debendra C. Baruah[2]

[1] *Tezpur University ,Tezpur, Assam, India*
[2] *Tezpur University ,Tezpur, Assam, India*
** Corresponding author. Tel: +913672267004, Fax: + 913672267005, E-mail: tapan_g@tezu.ernet.in*

Abstract: The present study analyzes the performance and combustion characteristics of 10%, 20%, 30% and 40% blending of Koroch Seed Oil Methyl Ester (KSOME) and Jatropha Methyl Ester (JME) with diesel as fuels in a diesel engine. The brake specific fuel consumption (BSFC) was more for the methyl ester blends and particularly for the JME blends. The brake thermal efficiency (BTE) was slightly lower for the biodiesel blends and for the JME blends it was less compared to that of the KSOME blends. The indicated power was more in case of the blends; however it reduced significantly for the 40% blend of KSOME. Both the KSOME and JME blends exhibited similar combustion trend with that of diesel, however, the blends showed an earlier start of combustion with shorter ignition delay. The ignition delay was less and the combustion duration was more for the JME blends as compared to the KSOME blends. The overall observation was that the KSOME blending up to 30% showed an acceptable performance and combustion trend whereas the JME blends showed favorable combustion trend but due its comparatively higher fuel consumption characteristics, finally the engine BTE was less with the JME fuel blends.

Keywords: *Biodiesel, diesel engine, Koroch seed oil, Jatropha*

1. Introduction

Biodiesel obtained from non edible plant species such as Jatropha *curcas (Ratanjot), Pongamia pinnata (karanj)*, *Calophyllum inophyllum (Nagchampa)*, *Madhuca indica* (*Mahua*), *Hevea brasiliensis* (*Rubber seed)* are gaining importance as possible renewable alternate fuels in India. Biodiesel is non toxic, biodegradable, and environmentally friendly as it contains minimum sulfur and aromatics. However, its higher viscosity leads to poor atomization of the fuel spray and incomplete combustion, coking of the injector tips, oil ring sticking and thickening and gelling of the engine lubricant oil. Its lower calorific value and lower volatility are regarded as its disadvantages. Therefore, the 5-20% (by volume) blending with standard diesel has been considered as suitable at present for using in existing diesel engines without any modifications. Many researchers have evaluated the performance of conventional diesel engines fuelled by bio-diesel and its blends. Raheman and Ghadge [1] while evaluating the performance of a single cylinder, four stroke Ricardo E6 engine with various biodiesel blends and pure biodiesel from Mahua seed oil found higher BSFC and lower BTE in case of the blends. Ramadhas et al. [2] used Rubber seed oil and its blend in a single cylinder diesel engine and observed that the blends containing 20–40% of rubber seed oil in the blend yielded an engine performance closely matching that of diesel oil. Raheman and Phadatare [3] used karanja methyl ester and its blends in a single cylinder, four-stroke, direct injection (DI) diesel engine and observed slightly higher torque in case of 20% blending (B20) and 40% blending (B40) while lower torque was observed with 60% blending (B60) to pure biodiesel (B100) when compared to diesel. BSFC was lower for B20 and B40 and found to be higher for blends ranging from B60–B100. The BTEs were also higher for B20 and B40. Sahoo and Das [4] made a combustion analysis using neat biodiesel from Jatropha, Karanja and Polanga; and their blends (B20 and B40) at various loads. Saravana et al. [5] observed lower delay period, lower maximum rate of pressure rise and heat release with 20% blending of crude rice bran oil methyl ester (CRBME) in a stationary small duty DI diesel engine. The BSFC of CRBME blend was found to be only marginally different from

that of the diesel. Qi et al. [6] evaluated combustion and performance of a single cylinder four stroke diesel engine (rated power 11.03 kW, rated speed 2000 rpm) with biodiesel produced from crude soybean oil. However, the performance and combustion trend vary depending upon the type of biodiesel used, engine configurations, test conditions, and the method of analysis. Also, the appropriate blend that would give optimum engine performance and best combustion characteristics may vary from biodiesel feedstock to feedstock, its production processes and the type of engine in which it is used. For the present investigation, biodiesel was prepared from Koroch seed and Jatropha curcus oil using a two step acid base catalyzed trans-esterification process in a laboratory scale. The properties of the various blends prepared by mixing biodiesel in various volumetric proportions with diesel obtained from Numaligarh refinery limited (NRL) are summarized in Table 1. The properties were determined at the Quality and Control Laboratory of NRL. Koroch is a tree found in abundance in the forests of north east India and oil obtained from Koroch seed has its own unique characteristics as a potential source of biodiesel. The author of this paper has not come across any study on diesel engine performance and combustion involving KSOME and its diesel blends. Although related literatures are available for JME, still blends of JME have been chosen as fuels for a comparative analysis.

Table 1. Properties of NRL diesel and various biodiesel blends

Fuel	NRL diesel	KB10	JB10	KB20	JB20	KB30	JB30	KB40	JB40
Density at 15°C (gm/cc)	0.8460	0.8500	0.8474	0.8548	0.8512	0.8594	0.8552	0.8661	0.8574
Kinematic Viscosity at 40°C (cSt.)	2.34	2.64	2.58	2.84	2.62	3.07	2.74	3.28	2.85
HHV (kJ/kg)	45553.0	45489.9	45682.4	45418.1	45471.9	45348.9	45379.0	45247.4	45161.2
Cetane index	46.60	46.34	47.48	46.50	48.01	46.34	48.54	45.39	48.61
Flash point (°C)	46	47	47	49	52	53	54	55	53
Pour point (°C)	3	-3	3	0	-3	3	-6	6	-6
Sulpher content (ppm)	489	440	452	390	370	302	308	274	292

2. Methodology

Tests were performed in a single-cylinder; four-stroke, naturally aspirated, DI diesel engine and its specifications are given in Table 2. T he test engine is provided with necessary instruments for combustion pressure, fuel pressure and crank-angle measurements. The in-cylinder and the fuel pressure are sensed by two piezo sensors. Signals from these pressure transducers are fed to a charge amplifier. A high precision CA encoder is used to give signals for top dead centre (TDC) and the CA. The signals from the charge amplifier and the CA encoder are supplied to a data acquisition system which is interfaced to a computer through engine indicator for obtaining pressure CA diagram. There are provisions in set up also for interfacing airflow, fuel flow and load measurement. The engine is coupled with an eddy current dynamometer for controlling the engine torque through computer. A Lab view based engine performance analysis software package evaluates the on line engine performance. The tests were conducted at steady state and 100% load at average engine speed of 1,535 rpm where the average engine torque was 21.85 Nm. This yielded an average brake power (BP) of 3.5 kW in each fuel test. Three test runs were performed under identical conditions to check for the repeatability of all the results. The repeatability of the results was found to be within an acceptable limit. The test results were then averaged and the average test results have been reported.

Table 2. Engine Specifications

Make and Model	Kirloskar –TV1
Rated power and speed	3.5 kW and 1500 rpm
Type of Engine	1 cylinder, DI type, 4Stroke
Compression ratio (CR)	12-18:1
IV Opening	4.5° before TDC
IV Closing	35.5° after BDC
EV Opening	35.5° before BDC
EV Closing	4.5° after TDC
Bore & Stroke	87.5mm and 110mm
Nozzle opening pressure	220 bar
Cooling Medium	Water cooled

3. Results and Discussion

3.1. Performance Characteristics

3.1.1. Brake thermal efficiency

Fig. 1 shows the BTE of the test engine for the tested fuels. It was observed that the BTE with the methyl ester fuel blends were comparatively less. The BTE decreased with increasing proportion of methyl ester in the blends. Further, the BTE for the JME blends were less compared to that for the KSOME blends. The BTE values with NRL diesel, KB10, JB10, KB20, JB20, KB30, JB30, KB40 and JB40 are 25.63%, 24.86%, 23.89%, 24.34%, 23.24%, 24.13%, 22.41%, 22.35% and 22.18% respectively. K and J here refer to KSOME and JME respectively. Compared to KSOME blends, slightly lower BTEs for the JME blends was mainly due to their increased fuel consumption rates for maintaining a constant BP output. Since the density and viscosity values of the JME blends were lower and the HHVs were higher compared to their corresponding KSOME blends, fuel consumption for the JME blends should have been lower than those of KSOME blends. Similarly the BTEs of the JME blends should also be more due to better combustion resulting from lower viscosities of JME blends compared to their KSOME counterparts. But the opposite trend in fuel consumption and BTE could not be understood. An energy balance study determining the various energy losses could be an appropriate future work for confirming this opposing trend.

3.1.2. Brake specific fuel consumption

The BSFC for the blends of JME and KSOME are compared with NRL diesel and is shown in Fig. 2. It was seen that the BSFC for the biodiesel blends was more. BSFC was marginally higher in case of the JME blends. This is due to higher fuel consumption rate in case of the JME blends. The fuel consumption rate for NRL diesel, KB10, JB10, KB20, JB20, KB30, JB30, KB40 and JB40 are 1.15 kg/h, 1.187 kg/h, 1.23 kg/h, 1.214 kg/h, 1.27 kg/h, 1.228 kg/h, 1.32 kg/h, 1.328 kg/h and 1.34 kg/h respectively.

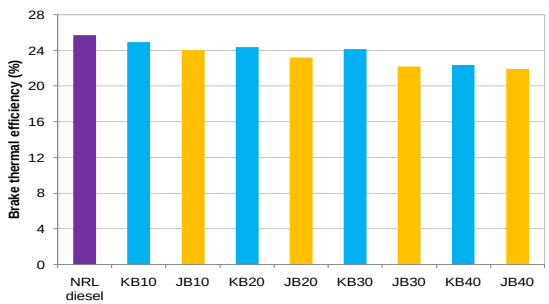


Fig. 1. BTE for the tested fuels

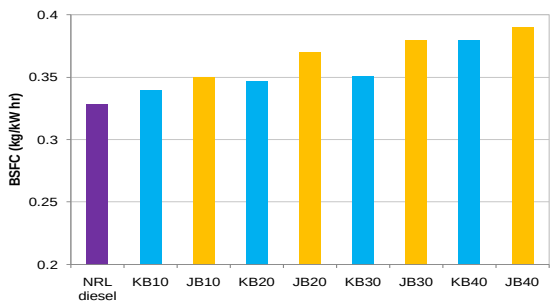


Fig. 2: BSFC for the tested fuels

3.1.3. Indicated power

From Fig. 3 it is observed that the engine IP operated with the blends is slightly more except for the blend KB40. The engine IP produced with NRL diesel, KB10, JB10, KB20, JB20, KB30, JB30, KB40 and JB40 are 5.6 kW, 5.76 kW, 5.7kW, 5.80 kW, 5.83kW, 5.92 kW, 6.02kW, 5.42 kW and 6.09kW respectively. It was observed that the loop work i.e. the work done during the gas exchange process and the compression work were less while the combustion and expansion work were more in case of the blends. Hence the net work done during the cycle was more and this resulted in higher IP. Slightly higher IP with the methyl ester blends may also be due to combustion of relatively more amount of fuel in case of the blends. Although the calorific values of blended fuels were lower than that of NRL diesel, the fuel energy was more for the blends and particularly for the JME blends due to relatively higher fuel consumption rate. Lower IP with KB40 was due to increase in the compression and loop works and decrease in the expansion work. The viscosity of KB40 was higher and may be due to poor combustion of this fuel blend it resulted in cylinder pressure variation leading to lower IP. Again, the IP with the JME blends was comparatively more than that with the KSOME fuel blends. It was due to higher energy input in respect of these blends and also due to higher net works done during the cycle as can be seen from the Table 3 shown below.

Table 3. Various works done during the cycle

Fuel	NRL diesel	KB10	JB10	KB20	JB20	KB30	JB30	KB40	JB40
Combustion and Expansion work (kJ)	724.13	728.18	721.84	719.64	734.99	743.05	748.1	692.86	749.90
Comprssion work (kJ)	309.80	300.51	285.98	286.15	288.43	294.92	288.63	311.35	280.55
Loop work (kJ)	24.16	20.12	10.42	18.32	8.48	14.64	13.84	42.97	8.55
Net work (kJ)	390.17	407.55	425.44	415.17	438.08	433.49	445.63	338.54	460.80

4. Combustion characteristics

4.1. Pressure crank angle diagram, peak pressure and rate of pressure rise

The pressure CA variation at full load is shown in Fig. 4 for the tested fuels. It was observed that pressure rise takes place early in case of the biodiesel blends. As compared to the KSOME blends, the pressure rise was earlier in case of the JME blends. Early pressure rise for the JME and KSOME blends may be due to their lower ignition delay which can be found out and will be discussed separately in section 3.2.4. Early pressure rise with JME blends in comparison to that with the KSOME blends implies relatively lesser ignition delay for the JME blends. It was also seen that more the amount of biodiesel in the blend, early is the pressure rise that occurs. Fig. 5 shows the peak cylinder pressure for the tested fuels. The peak pressure depends on the amount of fuel taking part during premixed combustion which in turn depends upon the delay period and the spray envelope of the injected fuel. Larger the ignition delay more will be the fuel accumulation, which finally results in a higher peak pressure. It was seen that the peak pressure for NRL diesel as well as the KSOME blends was almost the same at full load, the peak pressure values for KB10, KB20, KB30 and KB40 being 57.35, 57.62, 57.31 and 57.16 bar respectively, as against a peak pressure value of 57.43 bar for NRL diesel. However, the peak pressure for the JME blends were slightly less and these being 57.02, 56.98, 56.04 and 55.93 bar for JB10, JB20, JB30 and JB40 respectively. This is again due to combustion of relatively less amount of fuel during premixed phase of combustion as a result of lesser ignition delay period associated with the JME blends. The CAs at which these peak pressures occurred were 370, 370, 370, 370, 370, 369, 370, 369 and 369 degree CA for NRL diesel, KB10, JB10, KB20, JB20, KB30, JB30,

KB40 and JB40 respectively. Even though the pressure rise was occurring earlier in case of the JME and KSOME blends, but the peak values occurred almost at the same CA for these blends at full load. This may be due to lower rate of pressure rise in case of the biodiesel blends which is shown in Fig. 6. Rate of pressure rise was slightly more in case of the biodiesel blends towards the end of compression and it was more in case of the JME blends as compared to the KSOME blends. The pressure rise rate first decreased during the delay period for all the fuels and then it increased before the start of combustion (SOC) with a sharp rate of rise after SOC. However the peak of the rate of pressure rise was less and it also advanced in case of the biodiesel blends. Compared to the KSOME blends, the peak of the rate of pressure rise was less in case of the JME blends with early occurrence of the same.

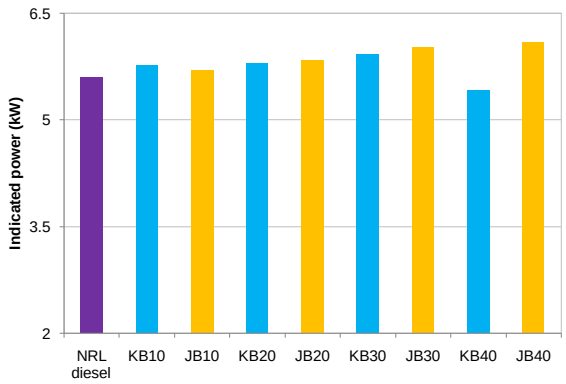


Fig. 3. Indicated power for the tested fuels

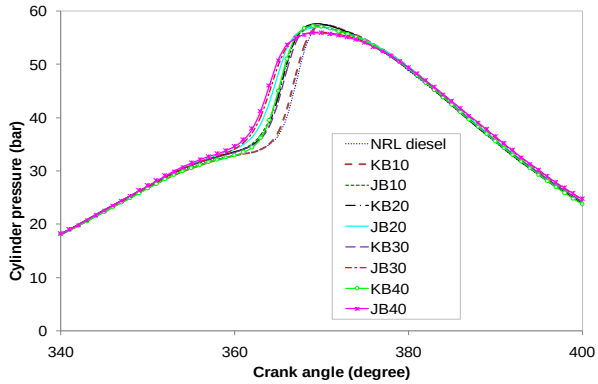


Fig. 4. Pressure crank angle variation for the fuels

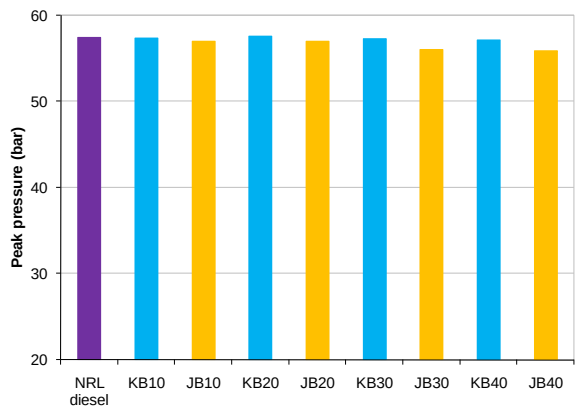


Fig. 5. Peak pressure for the tested fuels

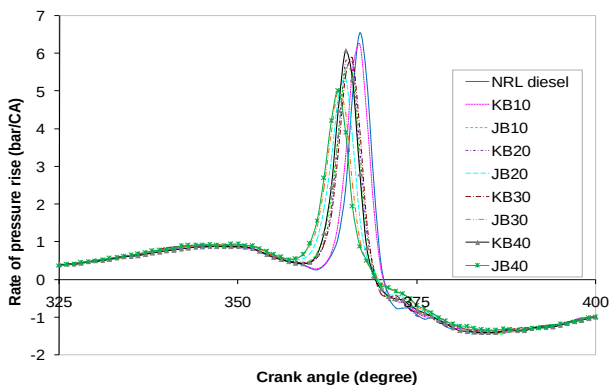


Fig. 6. Rate of pressure rise for the tested fuels

4.2. Net heat release rate

The heat release rate was calculated by first law analysis of the pressure CA data. The apparent net heat release rate which is the difference between the apparent gross heat release rate and the heat transfer rate to the walls is given by Equation (1) as given below.

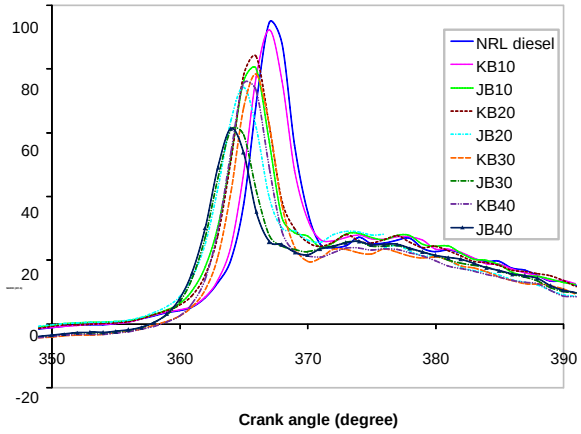
$$\frac{dQ_n}{d\theta} = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta} \qquad (1)$$

An approximate range for γ (specific heat ratio) for diesel engine heat release analysis is 1.3 to 1.35. However the values of γ which will give more accurate heat release information are not well defined [7]. In the present analysis value of γ for all the fuels were taken as 1.35. Lower heat release rate was observed in case of methyl ester blends at full load as can be seen from Fig. 7. In the equation (1), it is the second term in the right hand side which mainly influences it over a w ide range of TDC and therefore the rate of heat release is directly

proportional to the rate of pressure rise. Since the pressure rise was earlier in case of the biodiesel blends and also due to the early occurrence of the peak of the rate of pressure rise which was also lower for the blends it is seen in Fig. 7 that the net heat release rate also followed the same trend. As obviously the rate of net heat release raised early in case of the JME blends as compared to that of the KSOME blends. Similarly the peak of net heat release rate was also less for the JME blends. It was also seen that the net heat release rate was higher particularly for the JME blends during the reaction controlled diffusion and late combustion phases.

4.3. Cumulative heat release

Cumulative heat release is shown in fig. 8 for the tested fuels. It was observed that cumulative heat release was more for most of the biodiesel blends towards the later part of the combustion process which means that greater amount of heat was released in case of the blends for producing a given output. This was due to greater heat release as a result of diffusion combustion in case of the blends. As the amount of fuel taking part in combustion was more in the case of the KSOME and JME blends therefore it resulted in higher amount of heat release with the biodiesel blends. This is also the reason of higher IP associated with these blends. Although the calorific value of the KSOME and JME blends was less compared to that of NRL diesel but the lower calorific value of these fuel blends were compensated by their higher fuel flow rate and hence cumulative heat release increased in case of the blends. In case of the JME blends both the fuel consumption rates and the calorific values were more compared to their KSOME counterpart. Therefore the cumulative heat release was also more for the JME blends. Slightly lower cumulative heat release in case of JB10 was due to lower heat release during later part of its diffusion combustion. Exceptionally the cumulative heat release for the blend KB40 was significantly lower towards the later part of combustion. Although the fuel consumption rate was higher but may be due to incomplete burning of this particular fuel blend together with its lower calorific value it resulted in low cylinder pressure and low rate of pressure rise during the later part of combustion. This ultimately affected the cumulative heat release. The reason for incomplete burning can be its higher viscosity due to which it led to poor atomization and ultimately resulted in lower heat release. The same can also be the reason of lower engine IP produced with this particular fuel blend.



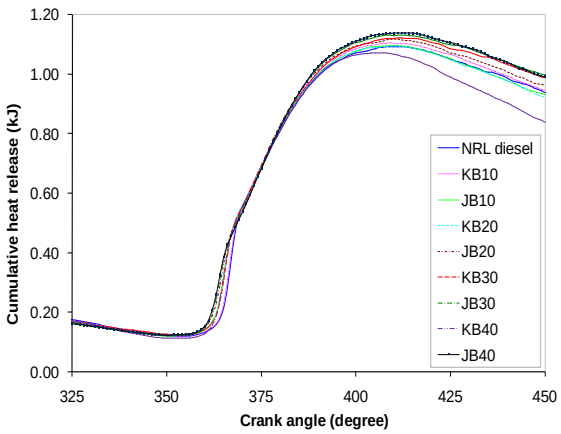


Fig.7. Net heat release rate for the tested fuels *Fig.8. Cumulative heat release for the tested fuels*

4.4. Igniton delay

Ignition delay is the time period between start of injection (SOI) and SOC. The point of SOI was determined from measurement of the fuel injection pressure profile. SOI is usually taken

as the time when the injector needle lifts off its seat. As no needle lift sensor was fitted to the injector, therefore the CA at which the fuel pressure in the fuel line reached its maximum value followed by a sudden drop in pressure, was considered as the SOI. Criterion based on max $\left(d^2 p / d\theta^2 \right)$ is widely used to predict SOC [7] and was also used in the present study to determine SOC. Fig. 9 shows the ignition delay for NRL diesel and various biodiesel blends at full load. It was found that the ignition delay period for the KSOME and JME blends was less. Further, the delay period was found to be less for the JME blends compared to the KSOME blends and the prediction made in pressure CA and heat release analyses was found to be correct. Cetane index of the KSOME and JME blends were higher and therefore the ignition delays were less for the biodiesel blends. Cetane index of the JME blends were comparatively higher and hence delay periods were lower for the JME blends compared to KSOME blends. Moreover, biodiesel typically contains unsaturated fatty acids and these get oxidized when exposed to oxygen environment. May be due to presence of higher oxygen content, biodiesel blends get ignited earlier than that of diesel. Another reason could be the rapid preflame chemical reaction of the biodiesel mixed fuel with high temperature air during injection and also the thermal cracking due to which the high molecular weight ester (biodiesel) breaks down to lighter compounds and ignites earlier resulting in shorter ignition delay.

4.5. Combustion duration

Determination of combustion duration of a diesel engine is a difficult task because the total combustion process consists of phases such as rapid premixed combustion, mixing controlled combustion and the late combustion of fuel present in the fuel rich combustion products. It can be defined as the time interval from the start of heat release to the end of heat release [4]. Banapurmath et al. [8] evaluated the combustion duration considering the CA interval between the SOC and 90% cumulative heat release. They observed higher combustion duration with Honge, Jatropha and Sesame oil methyl esters which they attributed to the longer diffusion combustion phase of the esters. Rao et al. [9] however observed lower combustion duration with JME blends and it was stated to be due to early start and faster rate of combustion. In the present study the CA at which the cumulative heat release is the maximum has been considered as the end of combustion. Fig. 10 shows the combustion duration for NRL diesel and the various methyl ester blends at full engine load. It was seen that, the combustion durations of KB30 and NRL diesel were the same (47° CA duration) and it was slightly less for the other KSOME blends. Even though the amount of injected fuel was more for the KSOME blends but slightly lesser combustion duration may be due to fact that biodiesel is oxygenated in nature which helps in early completion of combustion of the blends as it was the case for KB10. But with the increase in the amount of biodiesel in the blend, combustion duration increased for KB20 and KB30 which may be due to increase in the amount of fuel injected. But again the combustion duration decreased in case of KB40, which may be due to higher viscosity of this particular blend. However for the JME blends, the combustion durations were slightly more compared to the KSOME blends and these were 46, 47, 50 and 50° CA for JB10, JB20, JB30 and JB40 respectively. Slightly higher duration of combustion particularly with respect to JB30 and JB40 could be due to earlier start of combustion and relatively longer diffusion combustion for these blends.

5. Summary and Conclusion

Compared to NRL diesel operation, the KSOME and JME blends resulted in slightly poor performance in terms of BTE and BSFC. However the IP produced with the methyl ester

blends was more except for the blend KB40. Although the fuel consumption with KB40 was higher, but may be due to higher viscosity it resulted in poor fuel atomization leading to incomplete combustion, lower heat release and hence lower IP. All the blends revealed almost similar pressure CA characteristics, however early pressure rise and lower ignition delay was observed in case of the blends. Compared to the KSOME blends, the ignition delay period and the pressure rise were early in case of the JME blends. The JME blends also showed better combustion trend with improved rate of pressure rise and heat release due its lower viscosity, increased fuel consumption and slightly higher calorific value. However, BTE values were slightly lower for the JME blends.

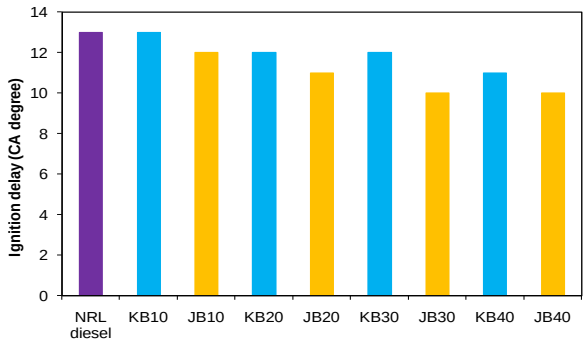


Fig.9. Ignition delay of the various fuels

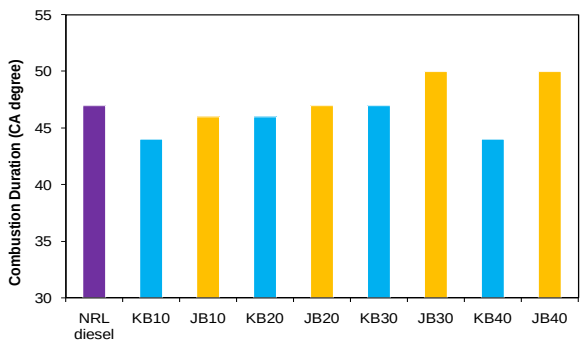


Fig. 10. Combustion duration of the fuels

References

[1] H. Raheman, S.V. Ghadge, Performance of compression ignition engine with mahua (Madhuca indica) biodiesel. Fuel 86 (2007) pp. 2568–2573

[2] A.S. Ramadhas, C. Muraleedharan, S. Jayaraj, Characterization and effect of using rubber seed oil as fuel in the compression ignition engines, Renewable Energy 30 (2005) pp. 795–803

[3] H. Raheman, A.G. Phadatare, Diesel engine emissions and performance from blends of karanja methyl ester and diesel, Biomass and Bioenergy 27 (2004) pp. 393 – 397

[4] P.K. Sahoo, L.M. Das, Combustion analysis of Jatropha, Karanja and Polanga based biodiesel as fuel in a diesel engine, Fuel 88 (2009) pp. 994–999

[5] S. Saravanan, G. Nagarajan, G. L. N. Rao, S. Sampath, Combustion characteristics of a stationary diesel engine fuelled with a blend of crude rice bran oil methyl ester and diesel, Energy 35 (2010) pp. 94–100

[6] D.H. Qi, L.M. Geng, H. Chen, Y.ZH. Bian, J. Liu, X.CH. Ren, Combustion and performance evaluation of a diesel engine fueled with biodiesel produced from soybean crude oil

[7] J.B. Heywood, Internal combustion engine fundamentals. New York: McGraw-Hill;1988.

[8] N.R. Banapurmath, P.G. Tewari, R.S. Hosmath, Performance and emission characteristics of a DI compression ignition engine operated on H onge, Jatropha and Sesame oil methyl esters. Renewable Energy 2008; 33:1982-8

[9] G.L.N. Rao, B.D. Prasad, S. Sampath, K. Rajagopal, Combustion Analysis of Diesel Engine Fueled with Jatropha Oil Methyl Ester - Diesel Blends. Int J of Green energy 2007; 4:645–58

Performance Study of a Diesel Engine by using producer gas from Selected Agricultural Residues on Dual-Fuel Mode of Diesel-cum-Producer gas

D.K.Das[1], S.P.Dash[2], M.K.Ghosal[1*]

[1] *Department of Farm Machinery and Power, College of Agricultural Engineering and Technology, Orissa University of Agriculture and Technology, Bhubaneswar-751003, Orissa, India*
[2] *Orissa Lift Irrigation Corporation, Government of Orissa, Orissa, India.*
** Corresponding author. Tel: +91 9556271208, E-mail: mkghosal1@rediffmail.com*

Abstract: Of all the alternative sources of energy for rural areas, producer gas from biomass appears to have the greatest potential. As an agricultural country, India has large supply of biomass resources. It is estimated that about 40 to 60 percent of agricultural residues are either lost or put to inefficient use. This calls for better utilization of these resources by thermo-chemically converting into producer gas in the current context of limitedness of petroleum based fuels for use in internal combustion engines. Diesel engines are widely used in Indian agricultural farms for a variety of stationary and mobile operations. The usual approach of producer gas utilization in diesel engines consists of operating existing compression ignition engines on producer gas cum diesel dual-fuel mode. There is also a lack of information on the use of different types and conditions of biomass to generate producer gas as a supplement fuel for diesel engines. Therefore, an effort was made to develop a gas producer system utilizing the locally available biomass materials to power a diesel engine that can be used on small horse power tractors and stationary machines. Experiments were conducted to study the performance of a diesel engine (four stroke, single cylinder, 5.25 kW) with respect to its thermal efficiency, specific fuel consumption and diesel substitution by use of diesel alone and producer gas-cum-diesel (dual fuel mode) through a downdraft gasifier. Performance of the engine was studied by keeping biomass moisture contents as 8%, 12%, 16%, and 21%, engine speed as 1600 rpm and with variable engine loads. The gas producer system developed for a 5.25 kW diesel engine was found to perform satisfactorily by using three types of biomass such as wood chips, pigeon pea stalks and corn cobs. The average value of thermal efficiency on dual fuel mode was found slightly lower than that of diesel mode. The specific diesel consumption was found to be 60 to 64 % less in dual fuel mode than that in diesel mode for same amount of energy output. The average diesel substitution of 64% was observed with pigeon pea stalks followed by corn cobs (63%) and wood chips (62%). Based on the performance studied, the producer gas may be used as a substitute or as a supplementary fuel for diesel conservation, particularly for stationary engines in agricultural operations in the farm.

Keywords: *Biomass gasification, Producer gas, Downdraft gasifier, Diesel engine.*

1. Introduction

The escalating oil prices and scarcity of fuel oils coupled with exploding population have resulted in serious energy crisis. There is thus a pressing need to develop technology for utilizing the renewable energy sources that can make significant contribution to the economy and the well being of the rural people.

Of all the alternative sources of energy for rural areas, producer gas from biomass appears to have the greatest potential. As an agricultural country, India has large supply of biomass resources. It is estimated that about 40 to 60 percent of agricultural residues are either lost or put to inefficient use. This calls for better utilization of these resources by thermo-chemically converting into producer gas in the current context of limitedness of petroleum based fuels for use in internal combustion engines. Producer gas is generated from solid carbonaceous fuels such as wood, charcoal, coal, agricultural and forest residues and also animal wastes by gasification process (Hindsgaul C et.al., 2000, Dogru M. et.al., 2000, Bhattacharya S.C. et.al., 2001, G. Sridhar et.al., 2001, Das and Pandey, 1993 and Pathak and Jain, 2004). Gasification is an irreversible thermo-chemical process by which feed stock is thermally decomposed and the end products are principally in gaseous form, the main combustible components being carbon monoxide and hydrogen. The main advantages of gases as a fuel over liquid or solid

fuels are that (i) gases burns with higher efficiency than the solid or liquid fuels, (ii) they have a higher rate of heat release (iii) the rate of energy output is easily controlled and adjustable, and (iv) gaseous fuels with good energy utilization can be used for power sources. A good quality producer gas has an energy content of about 5200 kJ/Nm^3. A gas producer requires 2.5 to 3 kg of wood to generate about the same energy as 1 liter of diesel (Tiwari and Ghosal, 2007).

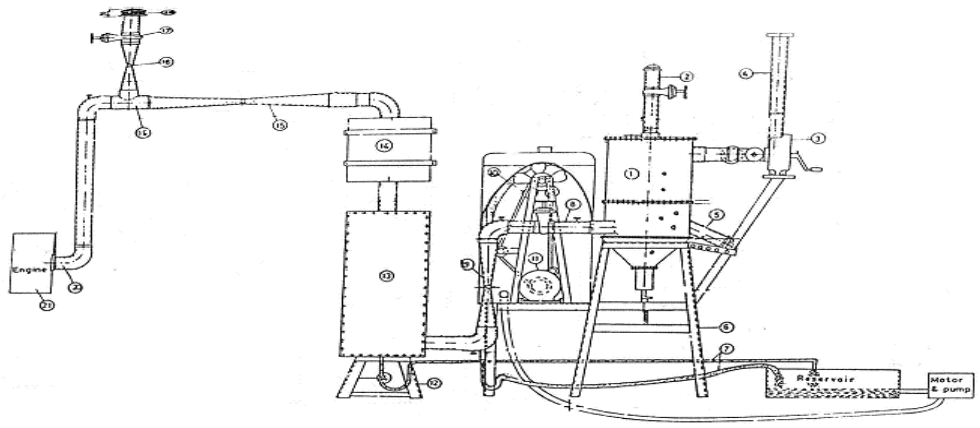
Diesel engines are widely used in Indian agricultural farms for a variety of stationary and mobile operations. The usual approach of producer gas utilization in diesel engines consists of operating existing compression ignition engines on producer gas cum diesel dual-fuel mode. The thermal efficiency of gasifiers in which producer gas is produced has been found to be 70-80 per cent and that of the gasifier-engine system to be 16-20 percent (Tiwari and Ghosal, 2007). The problem is more acute and serious in nature when producer gas is used to run motor vehicles particularly for agricultural operations. Past studies indicate that a very little effort has been made in this direction. There is also a lack of information on the use of different types and conditions of biomass to generate producer gas as a supplement fuel for diesel engines. Therefore an effort was made to develop a gas producer system utilizing the locally available raw materials to power a 5.25 kW (7 hp), single cylinder diesel engine that can be used on small horse power tractors, known as power tillers. The major objectives in this study were as follows:

(i) To fabricate the different components of a gas producer system to operate a 5.25 kW (7 hp) diesel engine.
(ii) To evaluate the performance of the above engine with respect to thermal efficiency, specific diesel consumption and diesel substitution by using different types of biomass.

2. Fabrication of gas producer system

A gas producer system consisting of a gasifier, a cooler cum cleaner unit, a filtration unit and a mixing device was designed and fabricated to operate a 5.25 kW diesel engine on dual fuel mode (Fig.1). A downdraft type gasifier operating under suction induced flow was designed for a maximum engine gas requirement of 10.70 Nm^3/h taking a maximum hearth load of 0.9 Nm^3/cm^2-h. The upper part of the gasifier was the fuel container and the lower part was the hearth with ash pit. The hearth section of the gasifier was V-shaped.

The primary air intake was through a pipe extended from top to the hearth with a provision to adjust the air inlet height. The ignition tube was passed through the hearth which was closed during gasification and opened only while starting to introduce fire. Ash pit was covered with a metal filter known as grate through which ash and soot particles were collected. A hand blower was attached to the gasifier for initial charging. The cooler-cum-cleaner unit consisted of a radiator to radiate heat from hot water, a venturi to provide sufficient space for cooling the gas and a water tank. The other attachments to the cooling system were a fan driven by a 0.375 kW motor to lift water from the tank to the radiator. A two stage filtering unit was developed to filter the dust and soot particles. The first stage consisted of gravel, charcoal, coconut coir and cotton layers each of 15 cm thickness where as the second stage consisted of only two layers of cotton each of 15 cm thickness. Both the filtering units were packed in different boxes.



1. Gasifier	8. Gas outlet	15. Gas flow venturi
2. Air inlet pipe	9. Gas cooling venturi	16. Air flow venturi
3. Blower	10. Radiator and fan	17. Air control gate valve
4. Blower outlet	11. Fan motor	18. Air filter
5. Ignition pipe	12. Filter stand	19. Air gas mixing device
6. Gasifier stand	13. Primary filter	20. Intake manifold
7. water pipe with U bends	14. Secondary filter	21. Diesel engine

Fig. 1 A gas producer system.

3. Methodology

A single-cylinder 4-stroke 5.25 kW diesel engine of a commercial power tiller was used for the experiment. The intake manifold of the engine was modified using a T-section to introduce the mixture of air and gas into the engine during suction stroke. The quantities of gas and air flowing to the engine were measured separately with the help of two venturi sections provided in the T-section. The U-tube manometers were connected to the venturi section with polythene tube to measure the pressure drop across them. The original fuel supply of the engine from its fuel tank was cut-off for the operation on dual fuel mode and the diesel fuel was supplied from an auxiliary tank provided with a fuel measuring set-up. In order to measure the load applied to the engine, a prony brake dynamometer was used. A strain gauge transducer was used to measure the temperatures of oxidation and reduction zones in the gasifier and the exit gas from the gasifier and the filtration unit.

3.1. Performance evaluation of engine

The diesel engine (specifications given in Table-1) was tested on diesel as well as on dual fuel mode at the engine speed 1600 r/min and six loads (7.5N, 12.5N, 20N, 30N, 40N and 50N). The composition of the gas was also studied (CO=22.8%; CO_2= 7.2%; O_2=0.5% and other gases= 69.50%). For dual fuel operation, the types of biomass used were wood chips, pigeon pea stalks and corn cobs. Three materials were used at four different moisture contents (8, 12, 16 and 21 percent on wet basis). Each test was conducted for a period of 5 minutes with two replications. During each test on diesel, the engine load, engine speed and fuel consumption were measured. The observed data were utilized to calculate the engine thermal efficiency, specific diesel consumption and percent diesel substitution. The performance of a diesel engine operated on dual-fuel mode was generally evaluated in terms of specific diesel consumption, engine thermal efficiency and per cent diesel substitution. These parameters were determined as follows,

a) Specific diesel consumption (SCD) : SDC is given by

$$\text{SDC} = \frac{3600 v_d \rho_d}{1000 t\ p} = 3.6 \frac{v_d \rho_d}{t\ p} \tag{1}$$

where SDC = specific diesel consumption, g $kW^{-1}h^{-1}$; v_d = volume of diesel consumed, cm^3, ρ_d = specific weight of diesel, kg/l; t = time required to consume v_d in second; and p = engine power, kw.

b) Thermal efficiency: The thermal efficiency is expressed as the ratio of output power to the power supplied by the fuel.

i) Thermal efficiency of engine on diesel alone: Thermal efficiency of engine on diesel alone is given by

$$\eta_t = \frac{\text{Brake power}}{\text{Power input from fuel}} \tag{2}$$

The power input from fuel in eqn. (2) is given by

$$p_f = \frac{cv_d \times \rho_d \times f_c}{3600} \tag{3}$$

Where p_f = Power input from fuel, kW; cv_d = calorific value of diesel = 39 MJ/kg ρ_d = densityof diesel = 640 kg/m^3; and f_c = fuel consumed, cm^3/h. Substituting the values of cv_d and ρ_d, the eqn (3) yields

$$\text{P}_\text{f} = \frac{39 \times 840 \times \text{f}_\text{c}}{3600} = 9.1\ f_c \tag{4}$$

Using eqn (4.), eqn (2) gives

$$\eta_t = \frac{Brake\ \text{power}}{9.1 f_c} \tag{5}$$

ii)Thermal efficiency of engine on dual fuel mode

The formula used for calculating the thermal efficiency of engine on dual fuel mode is given by

$$\eta_t = \frac{\text{Brake power}}{\text{Power input from pilot diesel} + \text{power input from gas}} \tag{6}$$

Power input from producer gas is given by

$$p_g = \frac{CV_g \times g_c}{3.6} \tag{7}$$

where p_g = power from producer gas, kW; cv_g = calorific value of producer gas, KJ/Nm^3; and g_c = gas consumption, Nm^3/h. Substituting eqns. (5) and (7) in eqn. (6),

$$\eta_t = \frac{Brake\ \text{power}}{9.1 f_c + \frac{CV_g \times g_c}{3.6}} \tag{8}$$

iii) Diesel substitution: The per cent diesel substitution is given by

$$ds = \frac{D_d - D_{dg}}{D_d} \times 100 \qquad (9)$$

Where ds = diesel substitution, per cent; D_d = diesel consumption by the engine on diesel alone, cm^3/h; and D_{dg} = diesel consumption by the engine on dual fuel mode, cm^3/h.

Table-1 Specifications of gas producer engine system under test

I. Engine		
(a)	Type	4-stroke cycle diesel engine
(b)	Number of cylinder	1
(c)	Cylinder capacity (cc)	450
(d)	Bore (mm)	80
(e)	Stroke (mm)	90
(f)	Crank shaft speed (rated), r/min	2200
(g)	Rated capacity (kW)	5.25
(h)	Grade of oil	SAE 30
(i)	Fuel	High speed diesel
(j)	Cooling system	Water-cooled
II. Gasifier		
(a)	Type	Moving bed, co-current Down draft
(b)	Material of construction	Mild steel
(c)	Hearth opening (mm)	60
(d)	Grate mesh size (mm)	10
(e)	Total weight (kg)	37

4. Results and discussion

The relationship between engine load and thermal efficiency at the four levels of moisture content (8%, 12%, 16% and 21%) for the different types of biomass (wood chips, pigeon pea stalks, corn cobs) is shown in Figs. 2 , 3 and 4 at engine speed of 1600 r/min. The trend shows that the thermal efficiency increased with a decreasing rate with increase in engine load for all the biomass fuels at all the biomass moisture levels tested. This may be due to better combustion of relatively rich gas-air mixture at higher loads. It is also observed that with increase in biomass moisture from 8 to 21 per cent, the thermal efficiency also increased marginally from 28 to 31 per cent with wood chips, 30 to 32 per cent with pigeon pea stalks and 29 to 32 per cent with corn cobs. The slight increase in thermal efficiency from 8 to 21 per cent moisture range might have been caused due to better combustion of premixed mixture of gas and air on dual-fuel mode resulting in reduced requirement of total energy input at different loads.

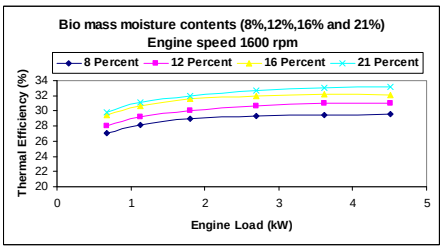


Fig. 2 Variation of thermal efficiency with engine load on dual fuel mode at different moisture contents of wood chips

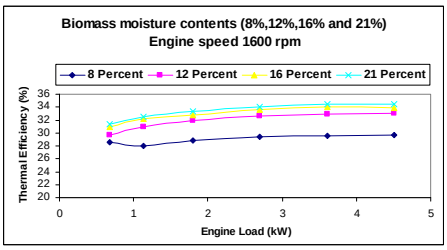


Fig. 3 Variation of thermal efficiency with engine load on dual fuel mode at different moisture contents of pigeon pea stalks

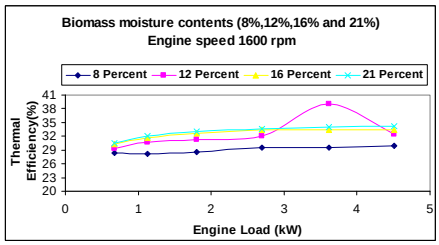


Fig. 4. Variation of thermal efficiency with engine load on dual fuel mode at different moisture contents of corn cobs

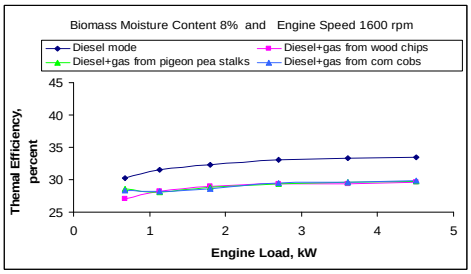


Fig. 5 Effect of engine load on thermal efficiency with different types of fuel

The effect of different types of fuel on engine thermal efficiency at 1600 r/min is shown in Fig. 5. The trend showed that there was a slight drop in thermal efficiency of engine on dual-fuel mode, compared to that on diesel alone. Based on mean values, it may be reported that the thermal efficiency of diesel engine when tested, dropped from 32.3 per cent on diesel fuel mode to 30.5 per cent on dual-fuel mode using wood chips. However, the efficiency of engine on dual-fuel mode using pigeon pea stalks and corn cobs was found almost at par with that on diesel mode. This showed that the combustion of air-gas mixture while using pigeon pea stalks and corn cobs was better compared to wood chips, even though the energy content of wood chips was relatively high. The variation of specific diesel consumption and diesel substitution with engine load on dual-fuel mode of a diesel engine at different biomass moisture levels has been shown in Figs. 6 through 11. The trend of the curves showed that the specific diesel consumption, in general, decreased with increase in engine load at different moisture levels for all the three types of biomass used. However, a definite trend of variation of diesel substitution with engine load has not been established. It has shown increasing trend with load in most of the cases, whereas in a few cases a decreasing pattern has also been observed. This kind of trend is not uncommon in the existing literatures. It is usually reported that if the energy content of the gas remains relatively stable, a higher load means a higher consumption of diesel fuel and thus a lower percentage of diesel fuel displacement. But if the quality of the gas in terms of its energy content is not stable, an increase in load can also increase the percentage of diesel fuel substitution. The decrease in specific diesel consumption with load is primarily due to increase in diesel fuel consumption at a decreasing rate. From the mean values of specific diesel consumption and diesel substitution in the test engine at different operational parameters (taking all loads into consideration), it was observed that the specific diesel consumption of engine on dual-fuel mode using wood chips decreased from 87.9 g/kWh at 8 per cent moisture level to 75.9 g/kWh at 12 per cent moisture level beyond which it again increased and rose to 161.8 g/kWh at a biomass moisture level of 21 per cent. The diesel substitution on the other hand, varied from 50.5 to 68.8 per cent in the same moisture range showing maximum value of 72.3 per cent at a moisture level of 12 per cent. Similar trends of variation of specific diesel consumption and diesel substitution were also noticed in case of the other two biomass fuels. For the sake of comparison, the minimum values of specific diesel consumption using pigeon pea stalks and corn cobs were observed to be 82 and 87 g/kWh respectively, whereas the maximum values of diesel substitution for these fuels was found to be about 71.3 per cent at a moisture level of 12 per cent. This showed that the minimum values of specific diesel consumption were derived at a particular biomass moisture level (12 per cent) where diesel substitution was maximum. This was perhaps due to better quality of gas obtained at this moisture level as reflected by its higher CO content resulting in better combustion of air gas mixture. The variation of specific diesel consumption with engine load for the test engine on diesel mode as well as on dual-fuel mode using different types of biomass is shown in Fig. 12 for a particular set of operating

parameters. The data indicated a slight decrease in specific diesel consumption with engine load both on diesel as well as on dual fuel operations. As expected, the specific diesel consumption on diesel mode is much higher than that on dual-fuel mode for all the engine loads tested. Comparing the performance of engine on the basis of the mean values of specific diesel consumption, it was observed that the engine consumed 60 to 64 per cent less diesel on dual-fuel mode than that on diesel mode for the same amount of energy output. The effect of engine load on per cent diesel substitution for different types of biomass is shown in Fig. 13. The trend showed increasing pattern of diesel substitution with engine load as explained earlier. Based on the mean values of diesel substitution, it can be pointed out that the average diesel substitution of 64 per cent was found with pigeon pea stalks followed by corn cobs (63 per cent) and wood chips (62 per cent) throughout the range of biomass moisture. From the results discussed above, it can be stated that the gasifier system developed for 5.25 kW diesel engine has indicated satisfactory performance by showing, on an average 60 to 65 percent saving in diesel consumption while utilizing three types of locally available biomass fuels.

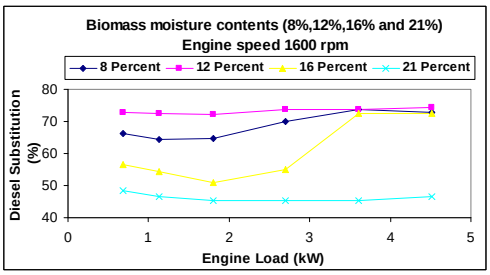


Fig. 6. Variation of specific diesel consumption with engine load on dual fuel mode at different moisture contents of wood chips

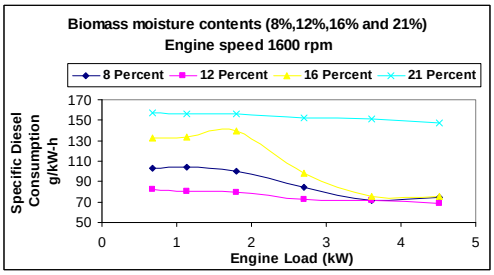


Fig. 7. Variation of diesel substitution with engine load on dual fuel mode at different moisture contents of wood chips

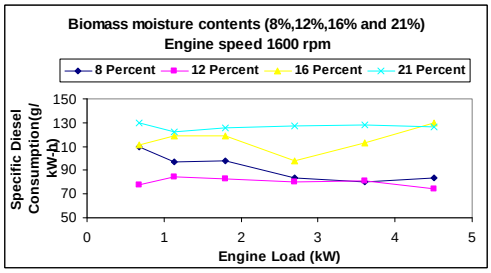


Fig. 8. Variation of specific diesel consumption with engine load on dual fuel mode at different moisture contents of pigeon pea stalks

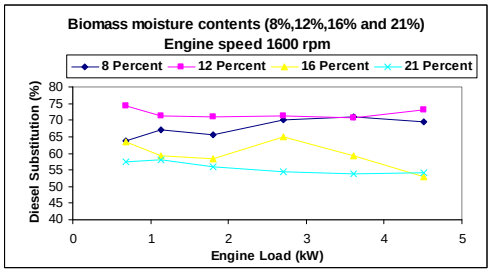


Fig. 9. Variation of diesel substitution with engine load on dual fuel mode at different moisture contents of pigeon pea stalks

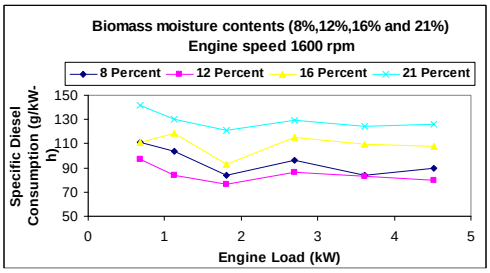


Fig. 10. Variation of specific diesel consumption with engine load on dual fuel mode at different moisture contents of corn cobs

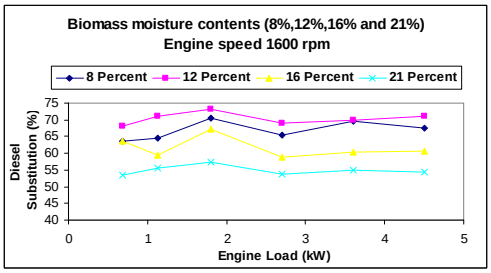


Fig. 11. Variation of diesel substitution with engine load on dual fuel mode at different moisture contents of corn cobs

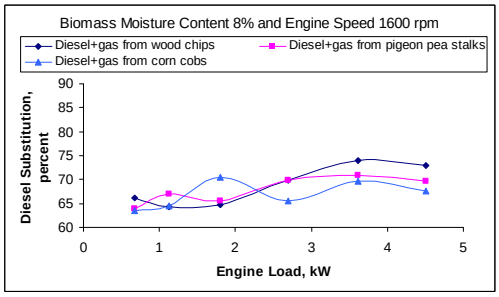


Fig. 12. Effect of engine load on specific diesel consumption with different types of fuel

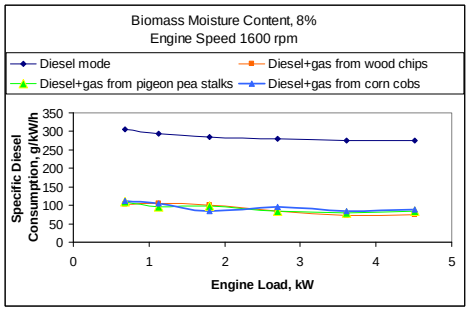


Fig. 13 Effect of engine load on diesel substitution with different types of fuel

5. Conclusions

Based on the studies conducted, the following conclusions may be drawn.

(i) The gas producer system designed and developed for a 5.25 kW diesel engine was found to perform satisfactorily by using different types of biomass such as wood chips, pigeon pea stalks and corn cobs.

(ii) The average value of thermal efficiency of engine was found to drop slightly from 32.3 percent on diesel mode to 28.7 percent on dual fuel mode using wood chips as biomass fuel. However the efficiency found on dual fuel mode with pigeon pea stalks and corn cobs was comparable to that on diesel mode.

(iii) The mean values of specific diesel consumption of engine on dual-fuel mode for all the three biomass fuels were less compared to diesel mode and their diesel substitution was more.

(iv) The average diesel substitution in a 5.25 kW diesel engine was found in the range of 62 to 64 percent using three types of biomass fuels.

The above findings presented in this paper would provide useful information to all those engaged in design, manufacture and use of gasifier system for satisfactory and mobile operation of stationary engine used in agricultural purposes.

References

[1] C. Hindsgaul, J. Schramm, L.Gratz, U. Henriksan, and J.D. Bentzen, Physical and chemical characterization of particles in producer gas from wood chips, Bio Resource Technology 73, 2000, pp. 147-155.

[2] M. Dogru, C.R. Howarth, G. Akay, B. Keskinler and A.A. Malik, Gasification of hazelnut shells in a downdraft gasifier, Energy, 27, 2000, pp. 415-427.

[3] S.C.Bhattacharya, Hla. San Shwe, and Hoang-Luang. Pham, A study on a multi-stage hybrid gasifier-engine system. Biomass and Bioenergy 21, 2001, pp. 445-460.

[4] G.Sridhar, P.J.Paul, and H.S.Mukunda, Biomass derived producer gas as a reciprocating engine fuel—an experimental analysis. Biomass and Bioenergy 21, 2001, pp. 61–72.

[5] D. K. Das, and K P. Pandey, Some studies on biomass based gas producer system for a diesel engine. Unpublished Ph.D. thesis, 1993, Agril.Engineering Department, IIT, Kharagpur.

[6] B. S.Pathak, and A. K.Jain, Engine quality producer gas from leucaena leucocephala and selected agricultural residues. J. of Agril. Engineering 21(3), 2004, pp. 43-50.

[7] G.N.Tiwari and M.K.Ghosal, Fundamentals of Renewable Energy Sources: Basic Principles and Applications. Narosa Publishing House, New Delhi, 2007.

Comparative Study on Performance of Straight Vegetable Oil and its FAME with respect to Common Diesel Fuel in Compression Ignition Engine

Soumya Sri Sabyasachi Singh[1], Dwijendra Kumar Ray[1], Sunasira Misra[2], Soumya Parida[2], Debendra Kumar Sahu[2,*]

[1]*Department of Mechanical Engineering*
[2]*Department of Chemistry, C.V. Raman College of Engineering, Bidyanagar, Mahura, Janla, Bhubaneswar-752054, India*
** Corresponding author. Tel:+91-674 2460043, 93, Fax: +91- 674 2460093, Email: drdksahu62@rediffmail.com*

Abstract: A comparative study has been carried out on the performance of compression ignition engine (CI) using common diesel fuel (CDF) blended with both refined soybean (Glycin max) and sunflower (Helianthus annus) oil as straight vegetable oil (SVO) as well as their corresponding fatty acid methyl esters (FAME) with respect to CDF. Low cost methyl esters of vegetable oil were prepared using own patented technique where ultrasonic energy has been found to be beneficial. SVOs and corresponding FAMEs were blended with CDF separately at different proportion to act as fuel for research CI engine. Both engine performance and fuel combustion characteristics were evaluated from the present study at different loads with varying compression ratios. Graphical relationships of load (kg) in engine against various engine performance parameters such as: brake thermal efficiency (%), brake specific fuel consumption ((kg/kWh), brake mean effective pressure (bar), cumulative heat release (kJ) and emission characteristics have been plotted for each set of fuels with respect to CDF. The relationship developed identifies the advantages of using blended FAME prepared with the patented processes over their corresponding SVO and CDF in the CI engine.

Keywords: *CI engine, Straight vegetable oil, FAME, Blended fuel, CDF*

1. Introduction

The Energy and Environment will determine the fate of mankind in this century. The alarming rise of energy demand in the growing civilization is mainly met by fast depleting fossil fuel. The transport sector is the highest consumer of fossil fuel as common diesel fuel (CDF) requiring more than 29 per cent of its total consumption. Due to its high sulphur, aromatics and nitrogen content the CDF is considered to be the single largest polluter of the environment. As the agro based vegetable oil is carbon neutral of renewable energy source and free of sulphur as well as aromatics, it behaves environmental friendly biofuel. However, the straight vegetable oil (SVO) fails to act as ideal fuel primarily because of its high viscosity and poor atomization in fuel spray for its low volatility. It often leads to deposit and chocking of injector, combustion chamber and valves [1]. These hurdles are reduced to minimum by subjecting the vegetable oil mainly to the process of dispersion or Transesterification. Dispersion of SVO with common diesel fuel, also called blending is to provide a simple as well as cheap fuel for the CI engine.

1.1. Transesterification of vegetable oil and animal fats

Chemically, vegetable oil and animal fat are triglycerides in which one glycerol molecule is esterified with three molecules of different long chain fatty acids [2] each with 15-20 carbon numbers raising its average molecular mass over 800amu. This reason might be responsible to inherit high kinematic viscosity and lowers vapour pressure. The process adopted to transfer one heavier ester to three lighter esters (esters of three different fatty acids with lower aliphatic alcohols) is called Transesterification reaction. Combination of these different

FAME molecules with viscosity and carbon equivalent to CDF is able to replace fossil fuel as ideal fuel for CI engine, popularly called Biodiesel [3].

1.2. Fuel for the performance of Unmodified Compression Ignition Engine:

CDF is a mixture of hydrocarbon molecules with varying carbon chain of C_6-C_{18}. The presence of smaller hydrocarbon chains with their high vapour pressure contributes to lower flash point of CDF to below 60^0C which is ideal to start ignition under common compression. While FAME of particular fatty acid (biodiesel), a compound of fixed carbon number 15-18 acquires very low volatility is contributing high flash point (>130^0C) thus fails to get atomized in unmodified CI engine for early ignition. The hurdle is minimized by blending the biodiesel with CDF. A system known as the "B" factor is generally used to state the amount of biodiesel in CDF fuel mixture such as: 100% biodiesel is referred to as B100, while 20% biodiesel when mixed with 80% CDF is labeled B20 and so on. Obviously, the higher the percentage of biodiesel, the more eco-friendly is the fuel. Blended fuel up to B20 has successfully used in unmodified engines [4-7].

The aim of the article is to evaluate the acceptability of biodiesel prepared at reduced parameters by employing ultrasonication at various steps of the composite process such as the purification of crude vegetable oil, transesterification, separation of FAME from the reaction mixture and purification of crude FAME to make ASTM standard. An unmodified CI engine setup with variable compression ratio is adopted to study the engine performance and combustion of fuel for different fuel and evaluate brake power (kW), brake thermal efficiency (%), brake specific fuel consumption (kJ/kW-hr), brake mean effective pressure (bar), of engine against various engine loads (especially lower loads). A comparative statement would be prepared for each set of four combinations of SVO-CDF, their corresponding FAME-CDF in different ration against CDF to find out the most acceptable fuel for the CI engine.

2. Methodology

2.1. Materials

Refined Soybean oil of Nature fresh (India) and refined sunflower oil of Fortune brand (India) are collected from retail outlets and analysed to evaluate the free fatty acid (FFA), phospholipids and moisture content following ASTM 6751 method. Refined varieties of soybean oil and sunflower oil were found to contain such impurities within permissible limit to prepare biodiesel. Fatty acid methyl esters (FAME) of refined soybean oil and sunflower oils were prepared following in house patented process [8]. CDF collected found to have the acceptable range of fuel specification for CI engine [9]. Low energetic (1kW) Ultrasonic Processor Sonapros PR-1000 model (M/s Oscar Pvt. Ltd., Mumbai, India) was used for transesterification at various steps of the composite process.

2.2. Preparation of fuels for the comparative studies

Four sets each of both soybean oil and sunflower oil were prepared by blending 5% and 10% of the two SVOs and their corresponding FAMEs with rest quantity of common diesel fuel (CDF). Samples of soybean and sunflower oil blends (as shown in ***Table 1***) were taken to evaluate the fuel properties in CI engine and make a comparative study with 100% CDF. Physical properties of this fuel were measured following ASTM 6751 method. Results within a range for both the fuels were reported in ***Table 2***.

Table 1. Set of fuels for the comparative study in CI engine

Vegetable oil	CDF %	Percentage of SVO in blended common diesel fuel		Percentage of FAME in blended common diesel fuel	
		05% SVO	10% SVO	05% FAME	10% FAME
Soybean oil	100	SVO SB B05	SVO SB B10	FAME SB B05	FAME SB B10
Sunflower oil	100	SVO SF B05	SVO SF B10	FAME SF B05	FAME SF B10

Table 2. Physical properties for Common Diesel Fuel (CDF), SVOs (soybean and sunflower oil) and corresponding methyl esters (Biodiesel)

Sl. No.	Properties of Fuel	CDF	Vegetable oil	Biodiesel
01	Kinematic Viscosity(cSt) at 40^0 C	2.5-5.5	35-65	5-8
02	Gross caloric value (kJ/kg)	42000	39,000-48,000	30000-39477
03	Density at 20^0 C, kg/m^3	0.835	0.825-0.894	0.865-0.877
04	Flash Point (^{0} C)	38	>200	130-175
05	Cetane Number	45	40-50	40-58

A Research engine, make Kirloskar type, 1 cylinder, 4 strokes diesel, water cooled with variable compression ratio (VCR) of M/s Apex Innovation Pvt. Ltd., Sangril, Maharashtra, India was procured to study the CI engine performance. The engine is of constant speed (1500 rpm) type having maximum load 12kg with a capacity of 661.1cm^3. The engine performance with various sets of fuels (shown in Table 1) was studied at lower loads of 2, 4, 6 and 8 kg under different compression ratios (16, 17 &18). The data acquisition system was used to create pressure-crank angle plot for both diesel and cylinder pressure. Also the pressure-volume plot was obtained to study the power generated by the engine at various compression ratios. Brake Specific Fuel Consumption and Brake Thermal Efficiency were obtained from load and fuel consumed etc. The engine Brake Power was measured by Eddy current dynamometer. Air inlet flow was measured using pressure transmitter and water flow by rotameter. Exhaust emission analysis was done with a multi gas analyser, M/s Netel (India) Ltd. under varying operating conditions.

3. Results and Discussion

3.1. Brake Specific Fuel Consumption (BSFC) of Soybean and Sunflower oil

Results on BSFC (i.e. the ratio of fuel mass flow of an engine to its output power) for all four sets of both soybean and sunflower fuel blends and CDF with engine loads of 2 to 8 kg against each compression ratio (16-18) are drawn but only CR 18 is shown in ***Fig. 1*** and ***Fig. 2*** respectively. It is observed that the BSFC(kg/kWh) is highest for B05 of both FAMEs when the engine load is only 2kg and CR 16, which further decreases linearly at higher CRs (17 and 18). BSFC for all fuels decrease uniformly when engine load increases to 8 kg because combustion improves due to increases in pressure and temperature.

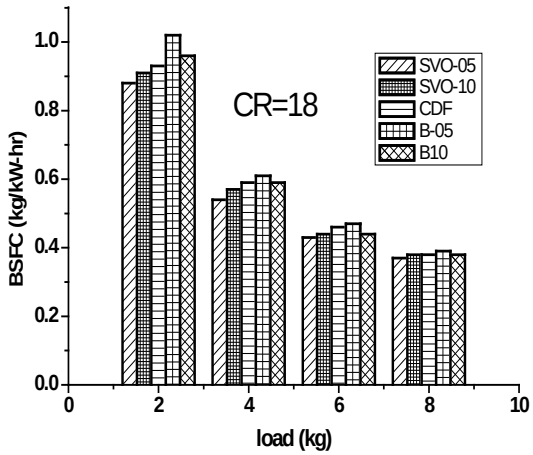


Fig.1. BSFC (kg/kWh) vs variable engine loads (kg) plot at CR-18 for four fuel blends of soybean oil and CDF

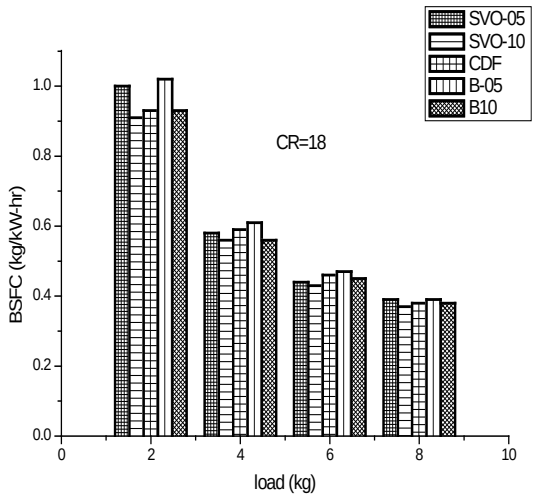


Fig. 2. BSFC (kg/kWh) vs variable engine loads (kg) plot at CR-18 for four fuel blends of sunflower oil and CDF

On comparing the results of ***Fig. 1*** (soybean oil) with ***Fig. 2*** (sunflower oil) it is observed that BSFC values for both fuel sets are almost identical at engine load 8 kg. Values for B10 of both fuel blends are less than that of B05 but almost equal to CDF. With low gross calorific values of biodiesel, it is expected to have high BSFC for the B10 blended fuel. The presence of easily combustible linoleic and oleic acids with unconjugated and unsaturated fatty acids in respective FAME probably balanced such negative effect.

3.2. Brake mean effective pressure for soybean oil and sunflower oil

Brake mean effective power (BMEP) is the measure of the useful power output of the engine and may be represented by the equation (1).

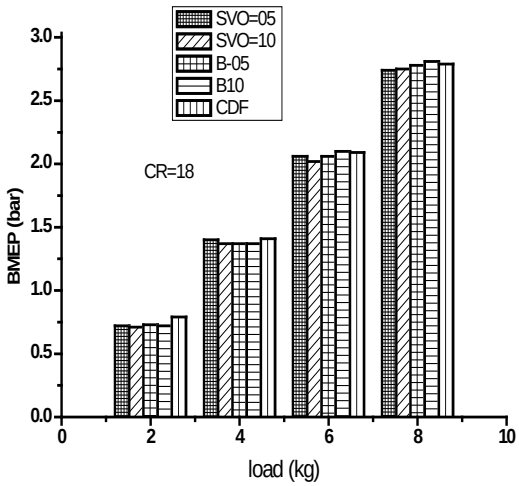


Fig. 3. BMEP (bar) vs variable engine load s(kg) plot at CR-18 for four fuel blends of soybean oil and CDF

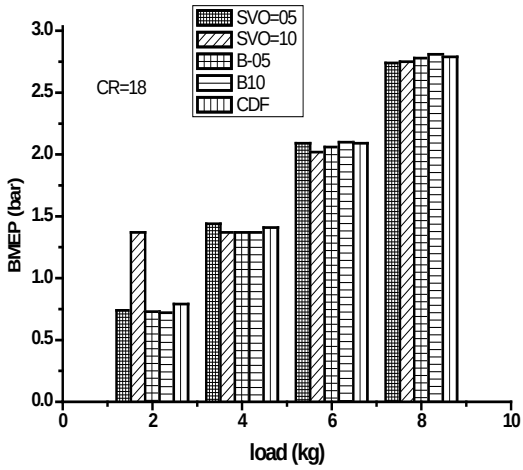


Fig. 4. BMEP (bar) vs variable engine loads (kg) at CR-18 plot at CR-18 for four fuel blends of sunflower oil and CDF

$$BMEP = 2\pi T n_C / V_d \qquad (1)$$

where T = torque(Nm), n_c = number of revolution per cycle and for 4 stroke engine it is 2, and V_d = displacement in volume.

Experimental results of brake mean effective pressure for each fuel of soybean set are drawn against engine load of 2-8 kg for each CR values of 16-18. The power outputs for all fuels are increasing with rise of engine load but shows same trend for all compression ratios. The BMEP comparison plots with respect to CDF at CR 18 for soybean and sunflower fuel blends are shown in ***Fig. 3*** & ***4*** respectively. BMEP is found to be much high for B10 of both soybean-FAME and sunflower-FAME at compression ratio 18 with 8 kg engine load.

3.3. Brake thermal efficiency

The variation of brake thermal efficiency with engine load of 2-8 kg at compression ratio 18 for both soybean and sunflower fuel sets are presented in ***Fig. 5*** and ***6*** respectively. It increases with increase in load under all compression ratios for both the fuel systems along with that of CDF. This may be due to the reduction in heat loss and increase in power with increase in load. The brake thermal efficiency for B05 and B10 for both fuel systems are less than that of CDF. This lower brake thermal efficiency obtained could be attributed to lower GCV values of biofuels. Hence it may be concluded that the performance of the unmodified CI engine with biodiesel prepared [10] with less operating parameter is comparable with conventional common diesel fuel.

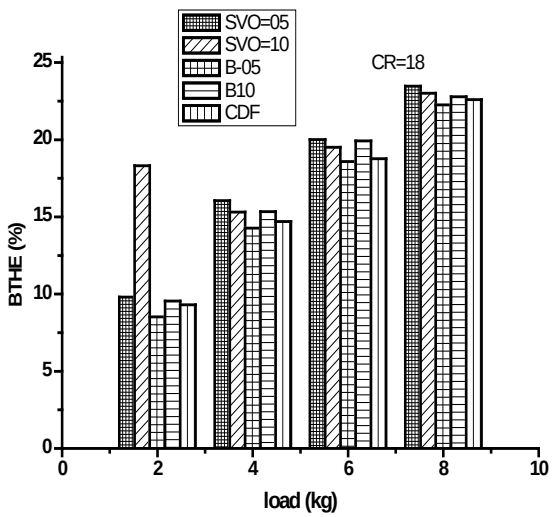


Fig. 5. BTHE (%) vs va riable engine loads (kg) plot at CR-18 for four fuel blends of soybean oil and CDF

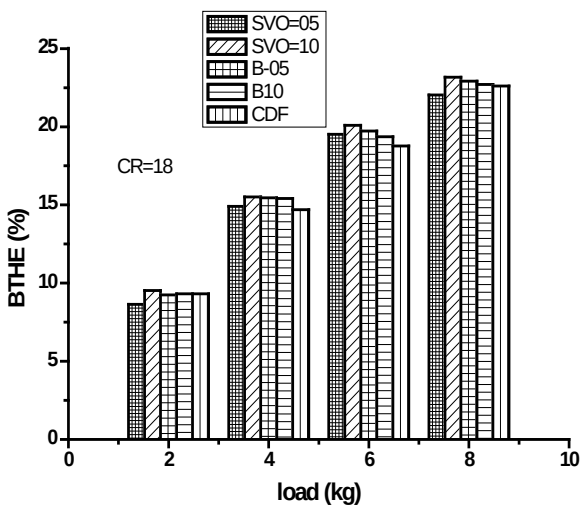


Fig. 6. BTHE (%) vs va riable engine loads (kg) plot at CR-18 for four fuel blends of sunflower oil and CDF

3.4. Brake power

The power output for all fuels increase with rise of engine load but shows same trend for all compression ratio at higher loads. ***Fig. 7*** shows FAMEs give slightly better power with respect to SVOs.

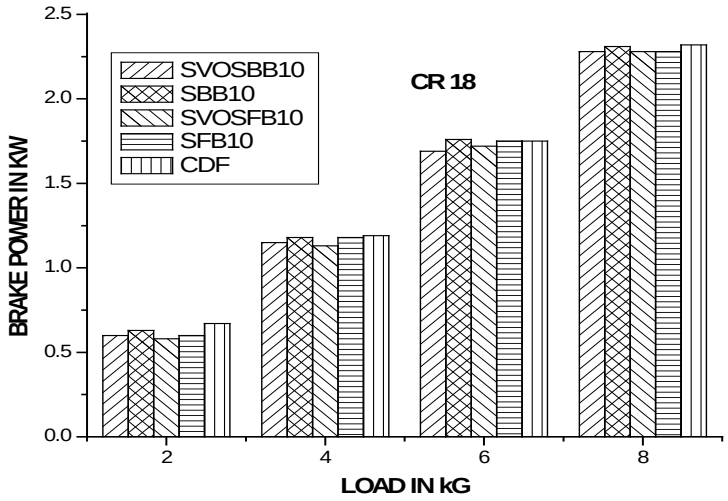


Fig.7. Brake power (kW) vs various engine loads (kg) plot at CR-18 for SVO and FAME (Biodiesel 10) fuel blends of soybean and sunflower oil with respect to CDF

3.5. Cumulative Heat Release

From ***Fig. 8*** it is clear that heat release of CDF is more than soybean SB B10 and slightly lower than sunflower SF B10 since biodiesels have less calorific value whereas out of these two biodiesels sunflower derivative is easily combustible than that of soybean.

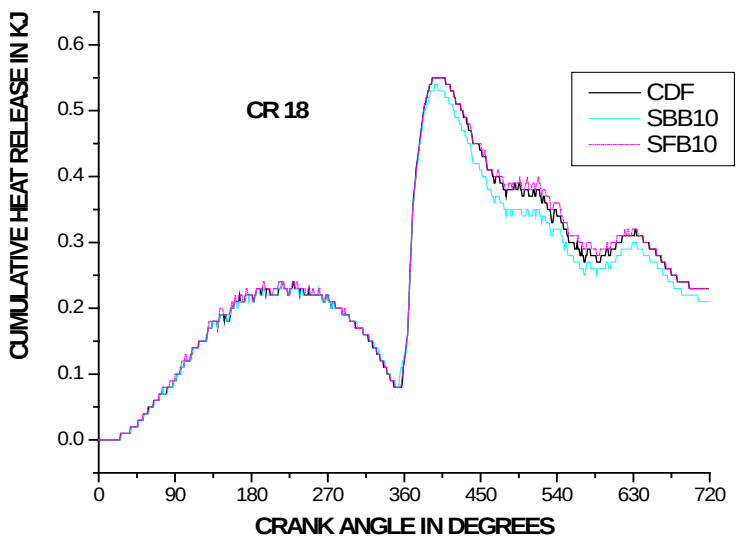


Fig.8. Cumulative heat Release (kJ) vs Crank angle (degrees) at 8kg engine load with CR-18 for CDF, soybean B10 and Sunflower B10

3.6. Exhaust emission characteristics

Exhaust emission profile for Common Diesel Fuel (CDF), and methyl esters (Biodiesel) of soybean and sunflower (B10) at CR 18 were studied and the results are given in Table 3. Combustion efficiency of these fuels under study increases with rise in engine load. It is seen that the combustion efficiency of B10 of both soybean and sunflower FAME are much better than that of CDF. SB B10 FAME is found to be more efficient fuel than SF B10. However, NO_x emission increases at higher loads due to rise in temperature in the compressor.

Table 3. Exhaust emission characteristics for Common Diesel Fuel (CDF), and methyl esters (Biodiesel) of soybean and sunflower (B10) at CR 18

Engine Load (kg)	CDF			Soybean (SB B10)			Sunflower (SF B10)		
	% CO_2	% O_2	NO_X (ppm)	% CO_2	% O_2	NO_X (ppm)	% CO_2	% O_2	NO_X (ppm)
2	1.7	18.2	72	2.9	16.1	144	2.4	17.2	106
4	2.0	17.5	116	3.5	15.6	235	2.8	16.6	162
6	2.6	16.8	161	3.9	15.0	290	3.1	16.1	226
8	2.9	16.2	208	4.6	14.0	321	3.4	15.7	269

4. Conclusion

The fatty acid methyl esters prepared from soybean and sunflower oil with own patented composite process employing ultrasonication has been successfully tested in unmodified compression ignition engine. Amongst various engine performance data evaluated, the BSFC parameters although suggest biofuel to be inefficient than CDF, however, considering the exhaust emission factor biofuel is acceptable. SVOs possess better performance, but taking the viscocity into account FAMEs look better fuel from the present study. From BMEP studies biofuels show better performance than CDF. With reference to the studies on BTHE, brake power and emission characteristics B10 soybean-FAME fuel is most acceptable fuel amongst the all studied nine fuels including CDF for the CI engine with lower load up to 8 kg at compression ratio 18. Hence it may be recommended as renewable fuel and prominent replacement for CDF in unmodified compression ignition engine.

References

[1] Meher L.C.,Vidyasagar D, Naik S.N., Technical aspects of biodiesel production by transesterification-a review. Renewable and Sustainable Energy Reviews10 2006, pp. 248-268

[2] Dmytryshyn S.L., Dalai A.K., Chaudhuri S.T., Mishra H.K, Reansey M., Synthesis and characterization of vegetable oil derived esters: evaluation for their diesel additive properties, Bioresource Technology 92, 2004, pp.55-6

[3] Ma F., Hanna M.A., Biodiesel production: A review, Bioresource Technol 70, 1999, pp.1-15

[4] Celikte, I., Koca, A., Arslan, M.A., Comparison of performance and emission of diesel fuel, rapeseed and soybean oil methyl esters injected at different pressure, Renewable Energy 35, 2010, pp. 814-820

[5] Sahoo, P.K., Das, L.M., Babu, M.K.G., Naik, S.N., Biodiesel development from high acid value polang seed oil performance evaluation in CI engine, Fuel 86, 2007, pp. 448-54

[6] Godiganur, S., Murthy Ch. S., Reddy, R.P., Performance of emission characteristics of a Kirloskar HA394 diesel engine operated on fish oil methyl ester, Renewable Energy 35, 2010, pp. 355-359

[7] Raheman H. and Ghadge S.V. Performance of Diesel engine with biodiesel at varying compression ratio and ignition timing, Fuel 87, 2008, pp. 2659-66

[8] Sahu D.K. and Parida S., A Process Technology for the Production of Low Cost Biodiesel, Indian Patent Application no- 165/KOL/2009 of dated 29.01.2009

[9] Diesel fuel ISI specification 1460, 1974

[10] Sahu, D.K. and Parida, S., Application of process of sonoication for single phase stability of straight vegetable oil-diesel blended fuel, presented in WREC2009-Asia, pp. 56

An Experimental Investigation on Performance and Emissions of a Multi Cylinder Diesel Engine Fueled with Hydrogen-Diesel Blends

Duraid F. Maki[1,*], P. Prabhakaran[2]

[1]*Mechanical Engineering Department, Faculty of Technology and Engineering, The M. S.University of Baroda Vadodara 390 002 – Gujarat - India*
** Corresponding author. Tel: +91 9974620190, E-mail:duraid_m@yahoo.com*

Abstract: Diesel engines are major contributors of air pollution by its exhaust gasses such as particular matter, carbon oxides, oxides of nitrogen, and sulfur compounds. Also, the diesel as a fossil fuel is threatened to decay with depletion of its sources. Hydrogen as a renewal energy and promising fuel might use to solve that troubles and crisis. A multi cylinder, natural aspiration, four stroke, compression ignition, and water cooled engine is tested under hydrogen diesel different blends and at different operating conditions. A hydrogen induction set up is built in the lab with all of the acquitting sensors and measuring instruments. The safety rules are considered. A continuous hydrogen induction in the inlet manifold is selected technique for this investigation. Experimental tests are done to investigate engine thermal performance and exhaust emission constituents under those blends circumstances. The optimum operating conditions and optimum parameters for those blends are found. The investigation led to find that, the optimum rate of hydrogen induction is 7.5 lpm. This optimum rate reduced the diesel fuel consumption by 20 % and increased the brake thermal efficiency by about 8-9%. The NO_X emission is reduced.

Keywords: *Hydrogen, Compression ignition engine, Performance, Exhaust emission, Dual Fuel.*

1. Introduction

Since 1878 to this day, diesel engine played the role of one primary source of power in human life. Many life sectors are depended on diesel engine such as agriculture and transportation. Diesel engine possesses a high reliability and durability with reasonable fuel consumption. Unfortunately, diesel engine is the main contributor to world's pollution. It has smoke and NO_X as major exhaust emissions. Numerous research efforts are concentrated on finding solutions to this problem. In 1970, the energy crisis ignited the competitions and research to find new energy sources or renewable energies. For both challenges, save our environment and save the energy sources, hydrogen is found as a promising solution. Hydrogen is nearly ideally suited as energy carrier because of its physical and chemical properties. It can be produced from water and conversely, on combustion forms water again in a closed cycle with very low formation of NO_X. It seems that the improvement in the engine performance under steady conditions is mainly attributed to the contribution of the hydrogen properties to the combustion process. The use of hydrogen with diesel engine might supplement wholly or partially without substantial hardware modification in arrangement of diesel engine [1]. The replacement of diesel by hydrogen totally needs high compression ratio above 29 along with a drop in the engine power and efficiency. Duel fuel mode or hydrogen diesel blends are more preferable [2]. The idea of using hot diesel drops as an igniter to air- hydrogen blend is applied. Many techniques have been studied and tested to inject or induct the hydrogen in air manifold or air intake passage. Carburetions, timing intake injection and induction, continuous injection or induction are the techniques mostly used [3].

Each technique has advantage and disadvantage. However, indirect injection or induction techniques pose no requirement of high compression ratio to run the engine under hydrogen-diesel blend. Verhelst at el. [4] used air port injection method to investigate the hydrogen effect on SI engine which might apply in diesel engine as well. Masood et al [5, 6] investigated direct injection and in port induction with modeling to those blends. Saravanan et

al. [7-10] investigated different techniques in the hydrogen injection and induction with recycling to exhaust gas and tested the timing and duration of hydrogen injection.

In this paper, a continuous induction of hydrogen in the air inlet manifold of a multi cylinder, compression ignition engine is adopted to investigate engine performance and exhaust gas emission constituents experimentally under different hydrogen induction rates and loads.

2. Experimental set-up

The experimental set up used for the present investigation consists of a four cylinder, four stroke, water cooled, indirect injection, naturally aspirated, and compression ignition engine developing a rated maximum power of 37 hp or 26.7 kW and running at varied speed equipped with a hydrogen induction system and an eddy current dynamometer with variable loading arrangement. The eddy current dynamometer gives the value of load in terms of Amp. only. The engine is coupled directly to the dynamometer and is mounted on a test bed with suitable connections for lubricating and cooling systems. The specification of the engine used for the study is given in Table 1.

Fig. 1 illustrates the schematic of the set up. Hydrogen induction system consists of high pressure hydrogen gas cylinder at 14.6 bar pressure, regulating valves, fine valve and digital mass flow meter to measure hydrogen flow rate. Nitrogen gas cylinder, flame arrestor, flame trap, non-return valve are used as a protection devices. PT 100 thermometer type is used to measure the exhaust temperature. Diesel weight flow rate is measured using strain gauge. Air surge tank with vertical water manometer is used to measure air pressure difference and to calculate the airflow rate in inlet manifold pipe. While a non contact tachometer is used to measure the engine speed. All the instruments are calibrated against traceable standards.

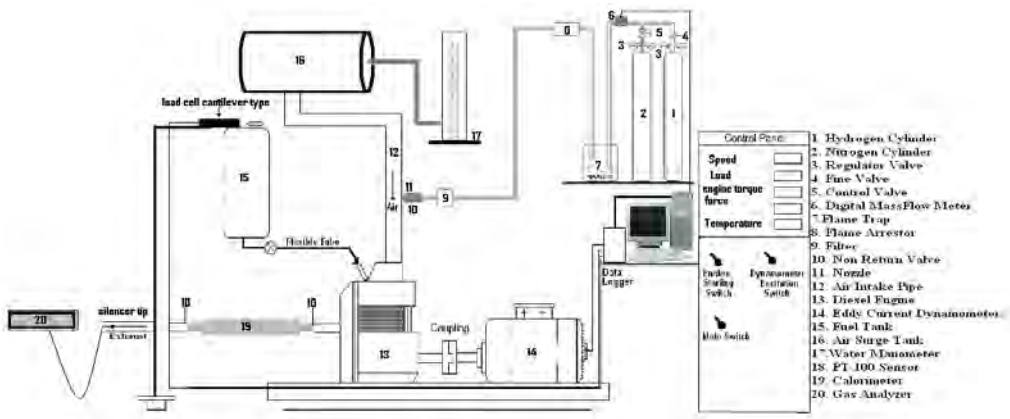


Fig. 1. The experimental setup

Table 1. Engine specification

Make and model	Stride Engine 1.5 E2 DSL
General details	Four cylinder, four stroke, compression ignition, vertical, water cooled, indirect injection
Bore	73 mm
Stroke	88.9 mm
Compression ratio	23:1
Max. power	27.6 kW @ 4000 rpm
Max. torque	83.4 Nm @2250 rpm
Capacity	1489 cm^3

3. Experimental procedure

The following step by step procedure is followed during the experimental investigation:
Start and run the diesel engine at 1500 rpm (most of previous investigations tested the diesel engine at this rate speed) for about 15 minutes to warm the engine and attain steady state condition before the data is acquired.

1. Set the fuel supply system in only diesel mode and record the data of fuel consumption rate, air difference pressure, engine speed, exhaust gas temperature, and exhaust gas constituents under no-load condition.
2. Repeat the observations under different load conditions at the eddy current dynamometer with loadings at 0.5, 1, 1.5, and 2 Amp. of load.
3. Run the engine on diesel mode. Then, set the induction of hydrogen in the an inlet manifold at a specified rate of 1 lpm and run the engine under dual fuel mode to attain steady state condition.
4. Record the data of fuel consumption rate, air pressure difference, engine speed, exhaust gas temperature, and exhaust gas constituents under 0.5 Amp. load condition.
5. Repeat the procedure in steps 4 and 5 under different load conditions at the dynamometer with loadings at 1, 1.5 and 2 Amp.
6. Repeat the experiment for different hydrogen induction rates of 2, 3,…, up to 18 lpm.
7. Close the hydrogen cylinder valve and open the nitrogen cylinder valve and purge the hydrogen gas from the induction system to avoid any burning of residual hydrogen gas.
8. Stop the induction of nitrogen and bring the engine to no load condition before switching off the engine.

4. Results and discussion

From an initial experimental study, it is found that the maximum rate of hydrogen induction at a given loading is to be restricted up to 18 lpm and the maximum loading possible on the engine is 2 Amp. due to engine load capacity restriction. This is the constraint within which the present experimental investigation is carried out.

Fig. 2 illustrates the relation between brake thermal efficiency and hydrogen induction rate at 1500 rpm speed and various loads. The brake thermal efficiency calculated by [1]:

$$brake\ thermal\ efficiency\ (\%) = \frac{Brake\ Power}{(m_f \times CV_D + m_{H2} \times CV_{H2})} \quad (1)$$

It is seen that, the brake thermal efficiency significantly increases with hydrogen induction rate. The rate of increase in brake thermal efficiency with continuous hydrogen induction is found to be higher at higher loads of 1, 1.5, and 2 Amp. load, while, there is no significant change in the efficiency with load of 0.5 Amp. The reason may be attributed to the higher caloric value of hydrogen which is approximately twice that of diesel. For a given load and speed condition, the influence of extra energy addition due to hydrogen induction on brake thermal efficiency is apparent from Eq. (1). The extra energy induction decreases the need of diesel fuel required. At full load, there is 20% increasing in brake thermal efficiency when the hydrogen induction rate changed between 0 lpm and 18 lpm.

Fig. 3 gives the variation in diesel fuel consumption with hydrogen induction rate for various loading (0, 0.5, 1, 1.5, and 2 Amp.) of diesel engine running at 1500 rpm. The engine running at constant speed needs less amount of diesel at a specified brake load due to extra energy available from hydrogen. It can also be noticed that the rate of reduction in diesel fuel consumption is higher at higher loading. At high load condition, the rate of reduction in diesel

fuel consumption is found to be about 40% between hydrogen induction rate from 0 to 18 lpm. This is observed to be true for higher loading of 1, 1.5, and 2 Amp. However, at no loading or light loadings of 0 and 0.5 Amp respectively, the reduction in diesel fuel consumption for hydrogen induction rate from 0 to 18 lpm is found to be about 25-30 %.

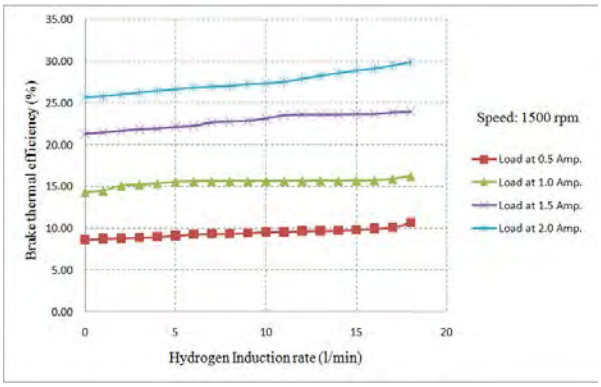


Fig. 2 Variation of brake thermal efficiency with hydrogen induction rate for various loading of diesel engine

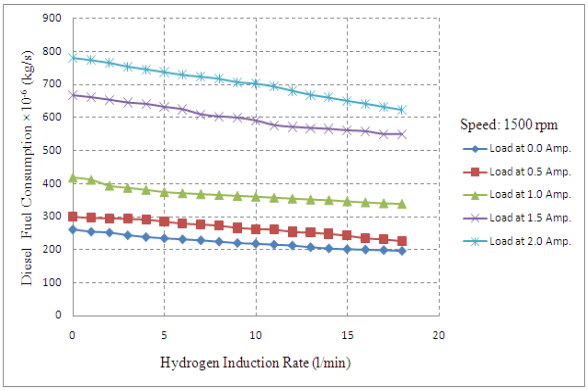


Fig.3 Variation of diesel fuel consumption with hydrogen induction rate for various loading of diesel engine

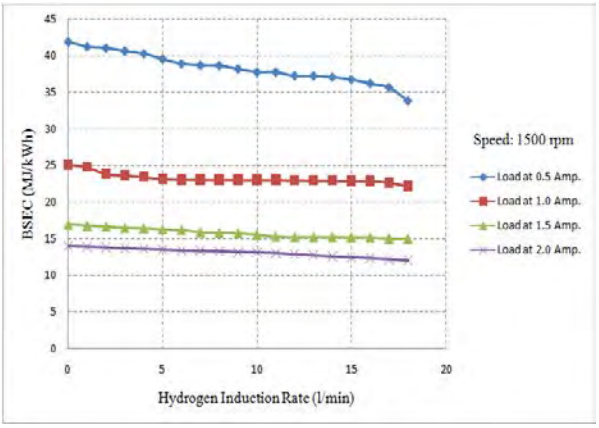


Fig. 4 Variation of brake thermal efficiencywith hydrogen induction rate for variousloading of diesel engine

The variation of the brake specific energy consumption (BSEC) with hydrogen induction rate at different loading conditions is shown in Fig. 4. It is seen that the hydrogen induction in the atmospheric air intake manifold of the engine enhances the consumption of energy to produce more usable power. Basically, the BSEC decreases with increase in load with the engine running at a given constant speed. The same trend is observed with various hydrogen induction rate also. With the induction of hydrogen, the decrease in BSEC is more significant when the load applied is beyond 1.0 Amp. At constant induction rate, the decrease in BSEC is of the order of about 3 times when the load is increased from 0.5 Amp. to 2.0 Amp.

Fig. 5 illustrates the effect of hydrogen induction rate on the exhaust temperature of diesel engine at different loading conditions with speed held at 1500 rpm. The increase in exhaust temperature is an indicator of combustion process behavior. The increment in exhaust temperature is directly indicating to the increment in the energy released increment in the combustion chamber. It can be noticed a margin increase in exhaust temperature due to the high caloric value of hydrogen.

The effect of hydrogen induction rate on volumetric efficiency is represented in Fig. 6. It is observed that irrespective of the loading condition, volumetric efficiency decreases by about 10% when the hydrogen induction rate increased from 0 to 18 lpm. The reason for such a trend may be attributed to the following. A naturally aspirated diesel engine working at a constant speed is found to operate with constant air suction rate. The rate of suction air decreases with increase of load resulting in a decrease of volumetric efficiency. In the range

of loading under consideration, the decrease is found to be a maximum of about 5%. However, at a constant speed and load, the volume intake of air decreases when hydrogen induction rate is increased which results in decrease of volumetric efficiency. The reduction in suction air rate leads to incomplete combustion affecting obviously the emission characteristics.

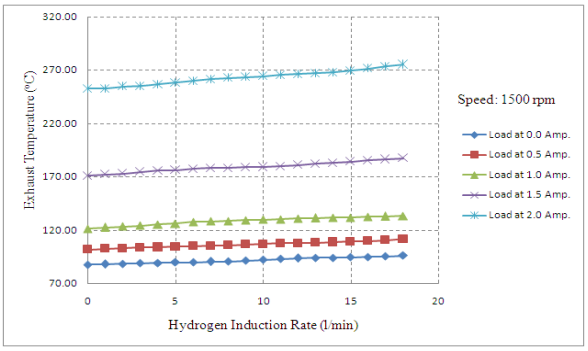


Fig. 5 Variation of exhaust temperature with hydrogen induction rate for various loading of diesel engine

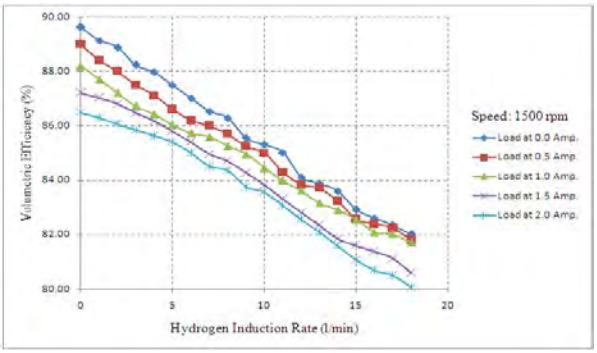


Fig. 6 Variation of volumetric efficiency with hydrogen induction rate for various loading of diesel engine

Fig. 7 shows the variation of equivalence ratio with continuous hydrogen induction rate for various loading of diesel engine running at constant speed. The trend is in consistent with that observed in Fig. 3. For diesel hydrogen duel fuel system, the equivalence ratio is calculated using Eq. (2) [12]. The equivalence ratio increases with loading increase. The equivalence ratio decreased as hydrogen induction rate increased for a given load.

$$\emptyset = \frac{\dfrac{[G]}{[Air] - \dfrac{[H_2]}{\left(\frac{[H_2]}{[Air]}\right)_{st}}}}{\left(\frac{[G]}{[Air]}\right)_{st}} \qquad (2)$$

Where, ϕ is equivalence ratio, [G], [Air], and $[H_2]$ are respectively diesel, air, and hydrogen molar concentrations. Subscript 'st' stands for stoichiometric. The thermal performance evaluation of the effect of continuous hydrogen induction in inlet manifold to naturally aspirated multi cylinder water cooled diesel engine running at a constant speed of 1500 rpm indicates improvement in brake thermal efficiency. The notable feature of the effect of the hydrogen induction is the significant reduction in diesel consumption rate required. However, an optimum hydrogen induction rate could not be ascertained for maximizing thermal efficiency and minimizing diesel consumption rate as hydrogen induction rate beyond 18 lpm poses serious flash back problems.

In view of the above observations, experimental investigations are further carried out to quantitatively estimate the emission characteristics and evaluate whether there should be an optimum hydrogen induction rate, which does not seriously affect pollutant emission rates. Figs. 8-12 represent the effect of continuous hydrogen induction rate on the emission of the various exhaust constituent gases such as CO, CO_2, HC, NO_X, and O_2 when the engine is run at different load.

It is seen from Fig. 8 that, the hydrogen induction rate has significant effect on CO emission. The reason for such a trend is due to the proportionate decrease in the content of inlet manifold air. In the case of fuel rich mixture, the CO emission increases while for that of lean

fuel mixture, it remains fairly constant. As diesel engines are operated with lean fuel mixture, CO emission is generally low [13]. However, with hydrogen induction rate increased from no induction to 18 lpm, the CO percentage emissions increases from about 0.15% to 0.95% with the loading of 2 Amp. Similarly, it is found that there is significant effect of hydrogen induction rate on CO emission for the engine running at 0, 0.5, 1 and 1.5 Amp. loads.

Since diesel consumption rate increases with increase in loading. There is an increase in CO_2 emission by about three times (i.e from about 2.5% to 7.5%) with no hydrogen induction. Further, similar trends are observed with hydrogen induction rate, Fig. 9. Further, it is seen that there is no significant effect on CO_2 emission when hydrogen induction rate increased from 0 to 18 lpm for engine running at constant speed and load.

Fig. 10 illustrates the effect of hydrogen induction rate on unburned hydrocarbon (HC) emission. It is observed that there is a considerable increase in HC emission when hydrogen induction rate is increased beyond 7.5 lpm. At 18 lpm hydrogen induction rate the HC decreased by about 8 times when the load varied between 0 and 2 Amp.

Hydrocarbons, or more appropiately organic emissions, are the consequence of incomplete combustion of the hydrocarbon fuel. The level of HC in the exhaust gases is generally specified in terms of total hydrocarbon concentration expressed in parts per million carbon atome or volume percentage (as in present work). While total hydrocarbon emission is a useful measure of combustion inefficiency, it is not necessarily a significant index of pollutant emissions. Engine exhaust gases contain a wide variety of hydrocarbon compounds. Hydrocarbon compounds are divided into different categories and scales. The simplest scale, which divides the HC into classes as methane and non methane hydrocarbons, probably best approximates the end result for all HC emissions. All hydrocarbons except methane react, given enough time. In diesel the HC constituents vary from methane to the heaviest hydrocarbons. The multi gas analyzer used into present work measured the HC on basis of the methane. Unburned hydrocarbons or partially oxidized hydrocarbons emission levels from diesel vary widely with operating conditions, and different HC formation mechanisms are likely to be most important at different operating modes. Engine idling or low speed and light load operations produce significantly high hydrocarbon emissions than full load or high speed operation [11]. These notes can be observed in the Fig. 10. The increment in hydrogen induction rate causes reduction in the intake air which results in a displacement of some volume of the intake air. With increase in load , therefore, the percent content of CO in exhaust gases slightly decreases for a given hydrogen induction rate. This slight reduction in per cent content of CO in exhaust gases may be either due to the formation of lean mixture when only diesel is used as base fuel or/and due to the conversion of CO to CO2.

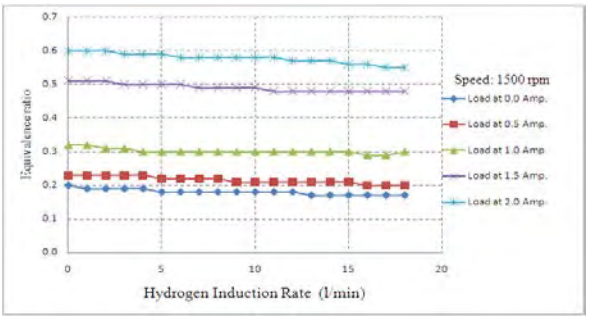


Fig. 7 Effect of hydrogen induction rate on equivalence ratio

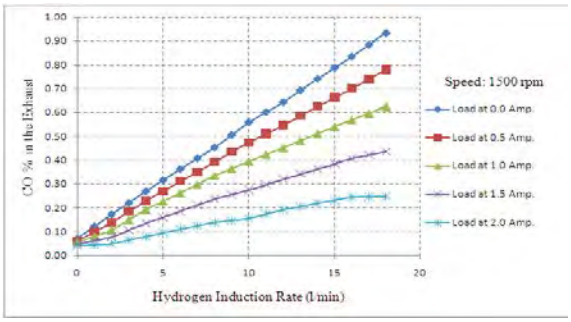


Fig. 8 Effect of hydrogen induction rate on on CO emission at difference loading

The effect of hydrogen induction rate on NO_X emission is given in Fig. 11. It is seen that there is 20% decrease in NO_X emission at smaller loading of 0, 0.5, and 1 Amp. from the condition of no induction to 7.5 lpm hydrogen induction rate. However, at higher loading, the decrease in NO_X emission is only about 6-7% between the same ranges of hydrogen induction rate. The constituent gases of NO_X emission are mainly NO and NO_2. Although the amount of the NO_2 is increased with higher hydrogen induction rate, the decrease in the amount of constituent gas NO plays a dominant role in the decrement in NO_X formation. The reduction in the amount of intake air has contributed to the reduction in NO_X emission in spite of the increase in the exhaust temperature. Fig. 12 illustrates the effect of hydrogen induction rate on O_2 emission. It is observed that there is only a marginal decrease in O_2 emission with increase in hydrogen induction rate. However, as the load on the engine is increased from 0 to 2 Amp., there is a 30 – 35 % decrease in O_2 emission.

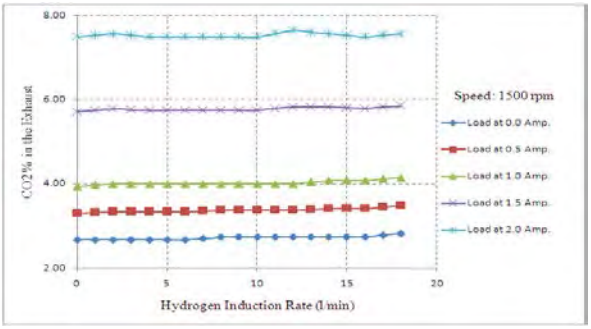


Fig. 9 Effect of hydrogen induction rate on CO_2 emision at difference loading

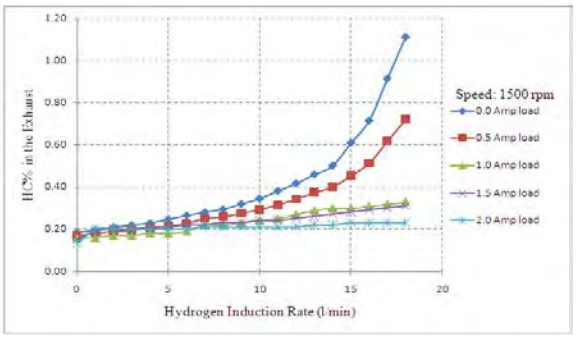


Fig. 10 Effect of hydrogen induction rate on HC emission at difference loading

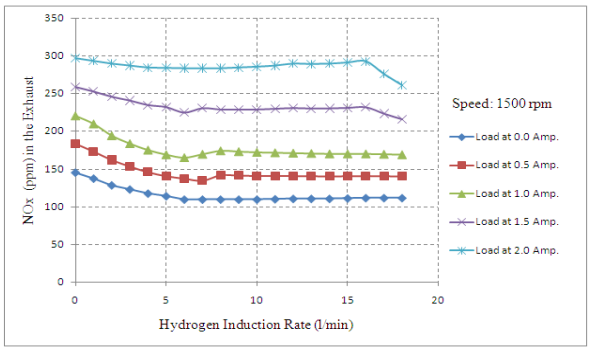


Fig. 11 Effect of hydrogen induction rate on NO_X at difference loading

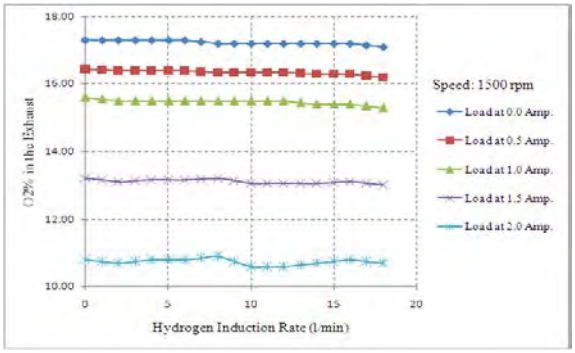


Fig. 12 Effect of hydrogen induction rate on O_2 emission at difference loading

5. Conclusion

Based on the experimental studies conducted on the thermal performance and pollutant emissions using a indirect injection multi cylinder naturally aspirated diesel engine with and without continuous hydrogen induction in the inlet manifold, the following conclusions are drawn:

1. A continuous hydrogen induction into the inlet manifold is a unique way of addressing simultaneously issues related to thermal performance and pollutant emission from diesel engine operated with diesel as a fuel. The system may be treated as hydrogen diesel dual fuel system as energy from hydrogen is also utilized.
2. There is a monotonous effect of continuous hydrogen induction rate on thermal performance parameters such as brake thermal efficiency, diesel fuel consumption rate and volumetric efficiency. And hence thermal performance tests alone cannot predict optimum hydrogen induction rate needed.

3. Based on both thermal performance and pollutants emission studies, it is seen that hydrogen induction rate about 7.5 lpm gives an optimum performance keeping the emissions level at a reasonable low levels. At 7.5 lpm, the levels of CO, CO_2 and HC are not increase significantly while the NO_X is reduced. The 7.5 lpm hydrogen induction rate approximately reduced the diesel fuel consumption by 20% and increased the brake thermal efficiency by about 8~9%.

References

[1] H. S. Yi, K. Min. and E.S. Kim, The Optimised Mixture Formation For Hydrogen Fuelled Engines, Int. J. of Hydrogen Energy, Vol. 25, Issue 7, 2000, pp. 685-690.

[2] Probir Kumar Bose and Dines Maji, An Experimental Investigation on Engine Performance and Emissions of a Single Cylinder Diesel Engine Using Hydrogen as Inducted Fuel and Diesel as injected Fuel with Exhaust Gas Recirculation Int. J. of Hydrogen Energy, Vol. 34, Issue 11, 2009, pp. 4847-4854.

[3] L. M. Das, Hydrogen Engine: Research and Development (R&D) Programmes in Indian Institute of Technology (IIT), Delhi, Int. J. of Hydrogen Energy, Vol. 27, Issue 9, 2002, pp. 953-965.

[4] S. Verhelst and R. Sierens, Hydrogen Engine Specific Properties, Int. J. of Hydrogen Energy, Vol. 25, Issue 9, 2001, pp. 987-990.

[5] M. Masood, S. N. Mehdi and P Ram Reddy, Experimental Investigation on a Hydrogen – Diesel Duel Fuel Engine at Different Compression Ratios, Transactions of ASME, Journal of Engineering for Gas Turbines and Power, Vol. 129, 2007, pp. 572578.

[6] M. Masood, M.M. Ishrat, A.S. Reddy, Computational Combustion and Emission Analysis of Hydrogen–Diesel Blends with Experimental Verification, Int. J. of Hydrogen Energy, Vol. 32, Issue 13, 2007, pp. 2539-2547.

[7] N. Saravanan and G. Nagarajan, An Experimental Investigation on Performance and Emissions Study with Port Injection Using Diesel as an Ignition Source for Different EGR Flow Rates, Int. J. of Hydrogen Energy, Vol. 33, Issue 16, 2008, pp. 4456-4462.

[8] N. Saravanan and G. Nagarajan, Performance and Emission Study in Manifold Hydrogen Injection with Diesel as an Ignition Source for Different Start of Injection, Renewable Energy, Vol. 34, Issue 1, 2009, pp. 328-334.

[9] N. Saravanan, G. Nagarajan, G. Sanjay, C. Dhanasekaran and K. M. Kalaiselvan, Combustion Analysis on a DI Diesel Engine with Hydrogen in Dual Fuel Mode, Fuel, Vol. 34, Issue 1, 2009, pp.328-334.

[10] N. Saravanan and G. Nagarajan, Experimental Investigation in Optimizing the Hydrogen Fuel on a Hydrogen Diesel Dual-Fuel Engine, Energy & Fuels, Vol. 23, 2009, pp. 2646–2657.

[11] Heywood, J.B., Internal Combustion Engine Fundamentals. 1988, New York: McGrew-Hill Book Company.

[12] Y. Hacohen and E. Sher, On the modeling of a SI 4-stroke cycle engine fueled with hydrogen enriched gasoline, Int. J. Hydrogen Energy, Vol. 12, No4., 1987, pp214-220.

[13] N. Saravanan, G. Nagarajan, K. M. Kalaiselvan and C.Dhanasekaran, An Experimental Investigation on Hydrogen as a Dual Fuel for Diesel Engine System with Exhaust Gas Recirculation Technique, Renewable Energy, Vol. 33, Issue 3, 2008, pp. 422-427.

Combustion Characteristics of an Indirect Injection (IDI) Diesel Engine Fueled with Ethanol/Diesel and Methanol/Diesel Blends at Different Injection Timings

Ali Turkcan [1], Mustafa Canakci [1, 2, *]

[1] *Department of Automotive Engineering Technology, Kocaeli University, 41380 Izmit, Turkey*
[2] *Alternative Fuels R&D Center, Kocaeli University, 41275 Izmit, Turkey*
**Corresponding author; Tel: +90 262 303 22 85, Fax: +90 262 303 22 03, E-mail:* mustafacanakci@hotmail.com

Abstract: In this study, the influence of methanol/diesel and ethanol/diesel fuel blends on the combustion characteristic of an IDI diesel engine was investigated at different injection timings by using five different fuel blends (diesel, M5, M10, E5 and E10). The tests were conducted at three different start of injection {25^o, 20° (original injection timing) and 15° CA before top dead center (BTDC)} under the same operating condition. The experimental results show that maximum cylinder gas pressure (P_{max}) and maximum heat release rate $(dQ/d\theta)_{max}$ increased with advanced fuel delivery timing for all test fuels. Although the values of P_{max} and $(dQ/d\theta)_{max}$ of E10 and M10 type fuels were observed at original injection and retarded injection (15° CA BTDC) timings, those of the diesel fuel were obtained at advanced injection (25° CA BTDC) timing. From the combustion characteristics of the test fuels, it was observed that ignition delay (ID), total combustion duration (TCD) and maximum pressure rise rate $(dP/d\theta)_{max}$ increased with advanced fuel delivery timing. The ID increased at original and advanced injection timings for ethanol/diesel and methanol/diesel fuel blends when compared to the diesel fuel. It was also found that increasing methanol or ethanol amount in the fuel blends caused to increase in ID and to decrease in TCD at all injection timings. At original injection timing, the $(dP/d\theta)_{max}$ increased with increasing methanol or ethanol amount in the fuel blends. To see the cycle to cycle variation, the fifty cycles of each fuel were also investigated at the different injection timings. It was found that, at the advanced injection timing, cyclic variability of the test fuels was higher when compared to the original and retarded injection timings. The maximum cyclic variability was observed with the M10 at the advanced injection timing.

Keywords: *Ethanol, Methanol, IDI diesel engine, Injection timing, Combustion characteristics*

1. Introduction

Compression ignition (CI) or diesel engines are widely used for transportation, automotive, agricultural applications and industrial sectors because of their high fuel economy and thermal efficiency. The existing CI engines operate with conventional diesel fuel derived from crude oil. It is well known that the world petroleum resources are limited and the production of crude oil is becoming more difficult and expensive. At the same time, with the increasing concern about environmental protection and more stringent government regulation, the researches on the decreasing of exhaust emissions and improving fuel economy have become a major research issue in the engine combustion and development. A lot of research related to the emissions reduction has been performed by using different injection parameters such as injection time and injection pressure, exhaust gas recirculation and oxygenated alternative fuels. In the recent years, methanol and ethanol are attractive oxygenated alternative fuels for diesel engines. The oxygenated alternative fuels such as methanol and ethanol have provided more oxygen during combustion. Therefore, the oxygenated alternative fuels and blends with gasoline and diesel fuel are more clean combustion processes than that of diesel and gasoline fuels [1-7]. The studies related to the alternative fuels should be enhanced for diesel engines especially for indirect injection (IDI) diesel engines. Because, they have a simple fuel injection system and lower injection pressure level. They do not depend upon the fuel quality and have lower ignition delay (ID) and faster combustion than direct injection (DI) diesel engines.

For a diesel engine, the fuel injection timing is a major parameter that affects the combustion and exhaust emissions. If the start of fuel injection timing is earlier, the initial air temperature and pressure will be lower, so that the ID will increase. The increase in the ID period causes to increase in the premixed burning phase, the cylinder gas temperature and the NO_x emissions. However, this trend decreases PM emissions. If the start of fuel injection timing is later (when piston is closer to TDC), the temperature and pressure will be slightly higher, therefore the ID will decrease. For this reason, injection timing variation has a strong effect on the combustion characteristics and exhaust emissions, because of changing maximum pressure and temperature in the cylinder.

Canakci et al. [2] experimentally investigated the combustion and exhaust emissions of a single cylinder diesel engine at three (25, 20 or iginal injection timing and 15° CA BTDC) different injection timings when methanol/diesel fuel blends were used from 0 to 15%, with an increment of 5%. The results indicated that the P_{max} decreased and the ID increased with the increase of methanol mass fraction at all injection timings. The increment in the ID caused to the deteriorating combustion thereby reduced the P_{max}. Also advanced injection timing boosted the P_{max} and the rate of heat release because of the increase in ID. Huang et al. [8, 9] used the diesel/methanol blend and combustion characteristics and heat release analysis in a CI engine. According to the experimental results, the increase in methanol mass fraction in the diesel/methanol blends resulted in an increase in the heat release rate at the premixed burning phase and shortened the combustion duration of the diffusive burning phase. The ID increased with increasing of the methanol mass fraction. This trend was more obvious at low engine load and high engine speed. TCD and P_{max} increased by advancing fuel delivery timing. The P_{max}, the $(dP/d\theta)_{max}$ and the $(dQ/d\theta)_{max}$ of the diesel/methanol blends obtained a higher value than that of diesel fuel. Yao et al. [10] researched the effect of diesel/methanol compound combustion (DMCC) fuel injection method on combustion characteristics. In this fuel injection method, the methanol was injected into the air intake of each cylinder. The diesel fuel was injected into the cylinder to ignite a methanol/air mixture. This system was tested on naturally aspired diesel engine. The test results showed that the ID increased and the cylinder gas temperature reduced with the DMCC fuel injection method due to the high latent heat of methanol.

Xing-cai et al. [11] conducted research on the heat release and emissions of a high speed diesel engine fuelled with ethanol/diesel blend. They found that the ID increased and TCD shortened for ethanol/diesel fuels when compared to diesel fuel. It was observed that the maximum heat release rate of ethanol/diesel blends were lower than that of diesel fuel. In the other studies, Rakopoulos C.D. et al. [12] investigated the effect of ethanol/diesel blends with 5%, 10% and 15% (by vol.) ethanol on the combustion and emissions characteristics of a high speed direct injection diesel engine. According to the experimental results, the ID for the E15 blend was higher than pure diesel fuel; also there was no significant difference among the P_{max} for each load conditions.

The combustion characteristics of IDI diesel engines are different from the DI diesel engines, because of greater heat-transfer losses in the swirl chamber. This handicap causes the brake-specific fuel consumption (bsfc) of the IDI engine to increase and the total engine efficiency to decrease compared to that of a DI diesel engine. Because of these disadvantages of the IDI diesel engines, most engine research has focused on the DI diesel engines. However, IDI diesel engines have a simple fuel injection system and lower injection pressure level because of higher air velocity and rapidly occurring air-fuel mixture formation in both combustion chambers of the IDI diesel engines. In addition, they do not depend upon the fuel quality and produce lower exhaust emissions than DI diesel engines [13].

From the literature review, it was concluded that the combustion characteristics of an IDI diesel engine have not been clearly investigated when using methanol/diesel and ethanol/diesel fuel blends at different injection timings. For this reason, this study experimentally investigated the effects of methanol/diesel and ethanol/diesel fuel blends on the combustion characteristics of an IDI diesel engine and compared them with those of diesel fuel.

2. Materials and method

In this study, a naturally aspirated, water-cooled, four cylinders IDI diesel engine was used as a test engine. The test engine specifications are compression ratio: 21.47, the maximum brake torque (95 Nm) was obtained at 2000 rpm and the maximum power 38 kW at 4200 rpm, start of injection timing: 20° CA BTDC and injector opening pressure: 130 bar. A hydraulic dynamometer was directly coupled to the engine output shaft. Fig. 1 shows the schematic diagram of the experimental setup. The following parameters were recorded during the each test: engine speed, load, fuel consumption, air flow rate, and ambient, cooling water inlet-outlet, and oil and exhaust temperatures. Conventional diesel fuel, methanol and ethanol were used, and their properties are shown in Table 1. To obtain cylinder gas pressure and fuel line pressure data, piezoelectric-type sensors were used. The cylinder gas pressure sensor was installed on the first cylinder of the engine head. The cylinder gas pressure was obtained by using a Kistler water-cooled piezoelectric sensor type 6061B. An AVL quartz pressure sensor 8QP500c was mounted on the fuel line of the first cylinder to measure the fuel line pressure. The outputs of the pressure sensors were amplified by a Kistler charge amplifier 5015A type. The output of the charge amplifier and a signal from the magnetic pick-up were converted to digital signals and recorded by an Advantech PCI 1716A data acquisition card, which has a 16-bit converter and 250 kS/s sample rate. The pressure and crank angle data were stored in a computer. A computer program was written to collect the pressure data, with a resolution of 0.25° of crankshaft angle. To analyze the cylinder gas pressure, a combustion analysis program was written. To eliminate cycle-cycle variation, the cylinder gas pressure data of 50 cycles were averaged using a computer program. Then, the pressure data was used to calculate the heat-release rate. Experiments were performed after the test engine reached to the steady-state conditions. The steady-state conditions were determined with the engine oil temperature (~70 °C). The test engine was run at least 5 min after the test engine was loaded, and then data was collected for each test. The test procedure was repeated 3 times to verify the each engine test condition, and the results were averaged.

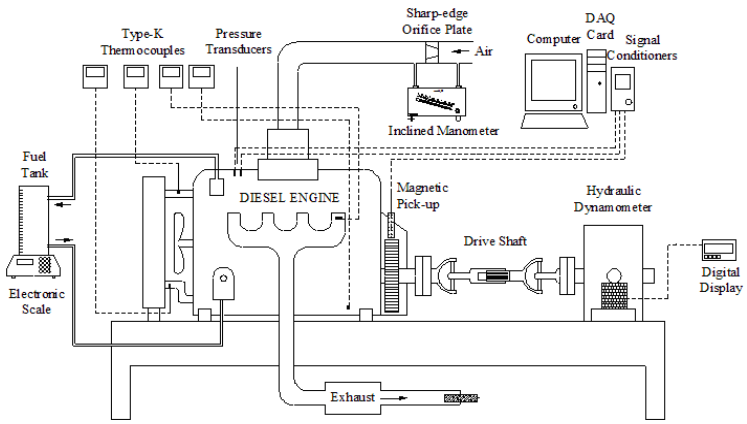


Fig. 1: Schematic diagram of the experimental set-up

Table 1. Properties of the test fuels

	Methanol	Ethanol	Diesel
Formula	CH_3OH	C_2H_5OH	$C_{10.8}H_{18.7}$
Molecular weight (kg/kmol)	32	46	170
Boiling temperature (^oC)	64.7	78	180 – 330
Density (g/cm^3, at 20 ^oC)	0.79	0.78	0.83
Auto-ignition temperature (^oC)	470	423	235
Lower heating value (MJ/kg)	20.27	26.8	43
Cetane number	4	5-8	50
Viscosity (mm^2/s, at 25^oC)	0.59	1.2	2.6
Heat of vaporization (MJ/kg)	1.11	0.856	0.280

3. Heat release analysis

The heat release analysis was based on the changes of the cylinder gas pressure and cylinder volume during the cycle. Therefore, some assumptions were made to calculate the heat release rate. It was assumed that no passage throttling losses exist between both chambers. Large temperature gradients, pressure waves, leakage through the piston rings, fuel vaporization and charge mixtures were ignored. Hence the intake and exhaust valves assumed to be closed. After using these assumptions, the heat release rate is calculated by using the following formula:

$$\frac{dQ}{d\theta} = \left[\frac{k}{k-1}\right] P \frac{dV}{d\theta} + \left[\frac{1}{k-1}\right] V \frac{dP}{d\theta}$$

Where: *(dQ/dθ)* is the combination of heat-release rate, *P* is cylinder gas pressure, *V* is cylinder volume, θ is the crank angle, k is the ratio of specific heats.

The parameters of combustion characteristics are ID, start of combustion, TCD which are obtained from heat release curve. The heat release curve in a diesel engine examines ID and TCD. The ID is defined as the time between the start of injection and the start of combustion. The start of injection time is determined by the fuel line pressure reached the injector nozzle opening pressure. The start of combustion is defined as the point where the heat release rate turns from negative to zero. The TCD is defined as the time from the start of combustion to the end of the heat release.

4. Results and discussion

In this study, the engine test was conducted at three different start of injection {25^o (advanced), 20° (original) and 15° (retarded) CA BTDC} under 1400 rpm and 40 Nm. The maximum fuel/air ratio was observed at 1400 rpm for diesel fuel, therefore the test condition was chosen as 1400 rpm. The relationship between the combustion characteristics and injection timings were focused by using conventional diesel fuel (D), E5, E10, M5 and M10. These fuel blends content of methanol or ethanol in different mass ratios (e.g., E5 contains 5% ethanol and 95% diesel fuel by mass). In this study, the combustion characteristics defined as the cylinder gas pressure and heat release rate were analyzed as shown in Fig. 2. The ID, TCD, $(dQ/d\theta)_{max}$, $(dP/d\theta)_{max}$, and the variation of the fifty consecutive P_{max} were also investigated as shown in Figures 3 and 4.

Fig. 2 illustrates the cylinder gas pressure and heat release rate of test fuels at three different injection timings under the same engine operating conditions. As shown in Fig. 2, it can be clearly seen that the cylinder gas pressure and heat release rate increased by advancing fuel

injection timings for all test fuels. This behavior was such that, as injection started earlier, the cylinder gas pressure and the heat release rate become higher due to more fuel injected during the ID period. In addition, the location of P_{max} and the start of combustion points occurred early with advanced fuel injection timing. Therefore the premixed combustion phases occurred earlier and also this phase finished before TDC at 25° and 20° CA injection timing. Diffusion or controlled combustion phase of the M10 and E10 formed lower burning than that of other test fuels at original injection timing. The lower viscosity and density of M10 and E10 led to high atomization and vaporization, so the lower burning was observed in the diffusion combustion phase. At the same time, the fraction of the heat release in the premixed or uncontrolled burning phase of the E10 and M10 blends decreased and the peak of premixed combustion phase of these blends increased at original injection timing. These results can be explained by increasing ethanol and methanol mass fraction in the blends.

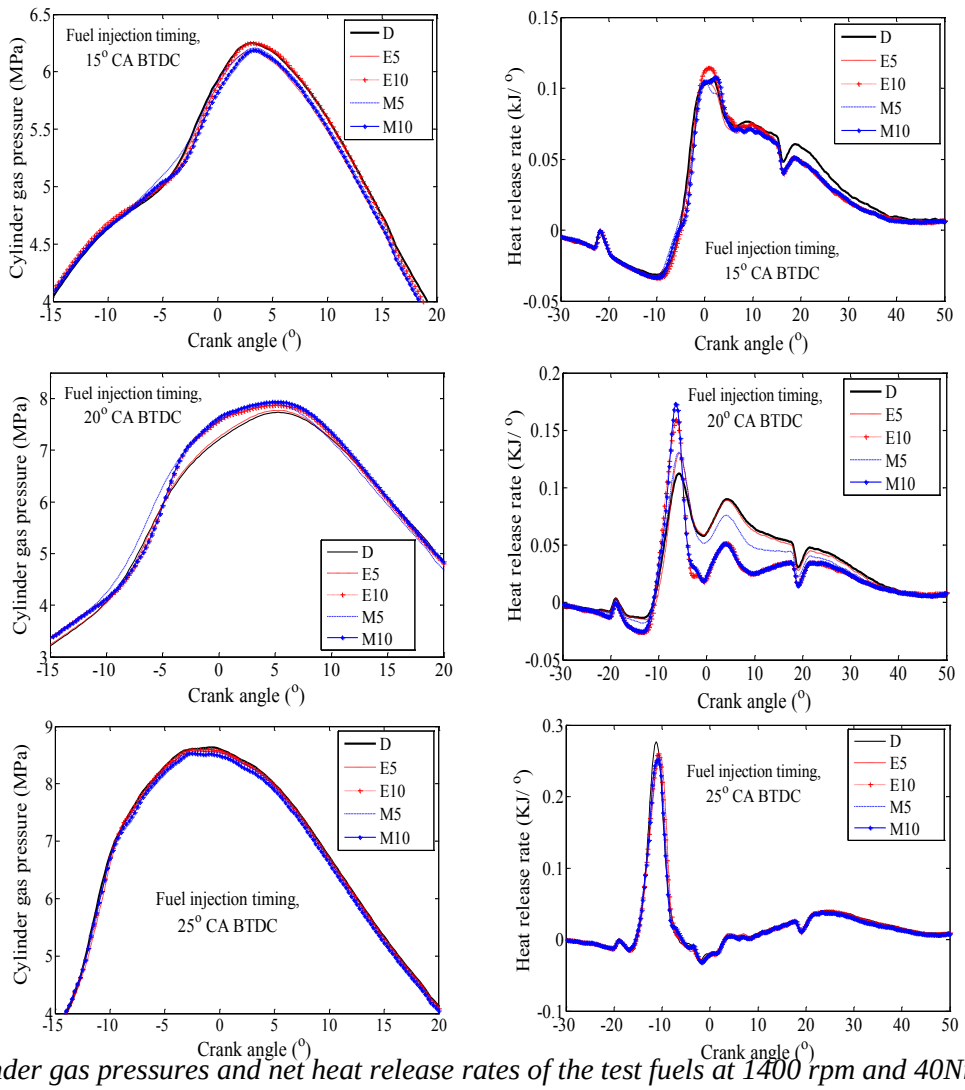


Fig.2 Cylinder gas pressures and net heat release rates of the test fuels at 1400 rpm and 40Nm

Fig. 3 shows the variation of ID, TCD, $(dQ/d\theta)_{max}$ and $(dP/d\theta)_{max}$ under three different injection timings. It was observed that the ID decreased with retarded injection timing for all test fuels. This behavior can be explained by the pressure, temperature and vaporization in the cylinder increased with retarded injection timings. It was found that, at advanced and original injection timings, the IDs of the blends are longer than that of conventional diesel fuel. This effect was interpreted by two different reasons. The first reason is that cetane numbers of the

blends which are lower than that of conventional diesel due to the cetane number decreased with the increase in methanol and ethanol mass fraction in the fuel blends. The second reason is that the methanol and ethanol have higher heat of vaporization than that of conventional diesel fuel. It was observed that the IDs of the E5 and M5 were shorter than that of E10 and M10 due to lower cetane number of the E10 and M10 blends. The TCD decreased with retarded fuel injection timing for all test fuels. The reason for the decrease in TCD is the increase in the premixed or uncontrolled combustion phase due to long ID and decrease in the diffusion or controlled combustion phase. It was revealed that, at all injection timings, TCD with blends was longer than that of conventional diesel fuel. This result can be explained by the increasing amount of the oxygen in the blends. It is known that the increase in amount of the oxygen enhances the combustion and causes to the diffusion combustion phase which becomes shorter.

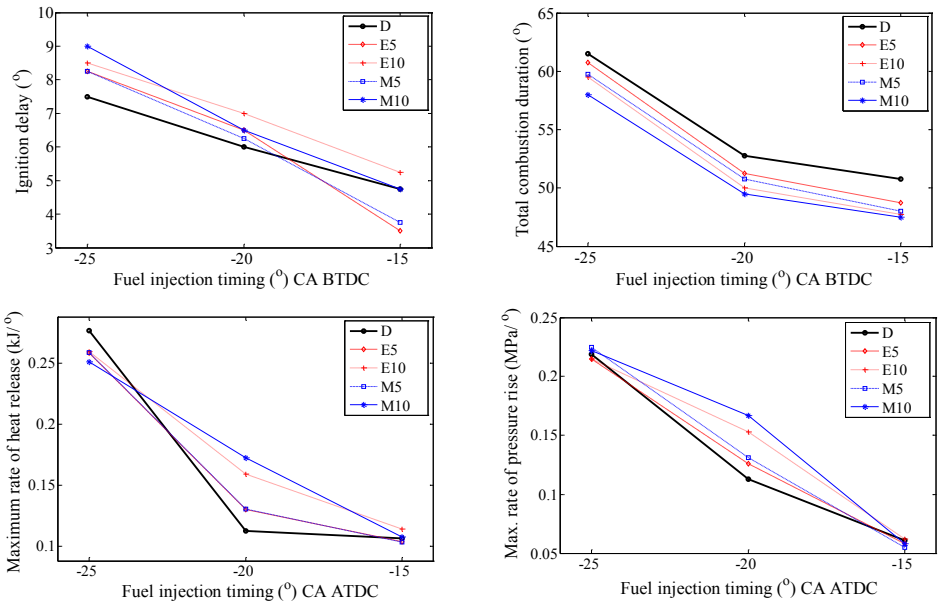


Fig.3 Effect of injection timing on the ID, TCD, $(dQ/d\theta)_{max}$ and $(dP/d\theta)_{max}$ at 1400 rpm, 40 Nm for each test fuel

As shown Fig. 2, the net heat-release profile has a slight negative dip during the ID period, which is mainly heat loss from the cylinder during the fuel vaporizing phase. It is more obvious at retarded injection timings. Because of the temperature in the cylinder increasing with retarded injection timing, the injected fuel during the ID period causes an increase in the evaporation heat. Therefore, the $(dQ/d\theta)_{max}$ decreased with retarded injection timings for all test fuels. The $(dP/d\theta)_{max}$ increased with the advancing injection timing as shown in the Fig. 3. This can be attributed to the increase in the injected fuel into the engine cylinder during the ID period, and so that produced higher the $(dP/d\theta)_{max}$ and the cylinder gas pressure. Also, there is no significant difference among the $(dQ/d\theta)_{max}$ and the $(dP/d\theta)_{max}$ of the test fuels at advanced and retarded injection timing, while at original injection timing, the $(dQ/d\theta)_{max}$ and the $(dP/d\theta)_{max}$ of the blends were higher than that of conventional diesel fuel. The main reason for this situation is that in order to obtain the same bmep from the blends, more fuel was injected into engine cylinders due to the blends have lower heating value than that of conventional diesel fuel. At the same time, it w as observed that the $(dQ/d\theta)_{max}$ and the$(dP/d\theta)_{max}$ increased with the increase in the mass fraction methanol and ethanol in the blends at original injection timing. This was caused by E10 and M10 fuel blends which have

more oxygen rate than E5, M5 and conventional diesel fuel. Thereby, the combustion became better and the $(dQ/d\theta)_{max}$ and the $(dP/d\theta)_{max}$ increased.

Fig. 4 shows the average of the P_{max} achieved from 50 consecutive cycles for all test fuels and all injection timings. It was observed that the cyclic variability decreased with the retarding fuel injection timings. Specially, at 25° CA injection timing, the cyclic variability of the M10 test fuel was higher than those of other injection timings. As shown in Fig.4, similar cyclic variability and the smooth operation of the engine can be achieved by using E5, E10, M5 and M10 blends when compared the conventional diesel fuel.

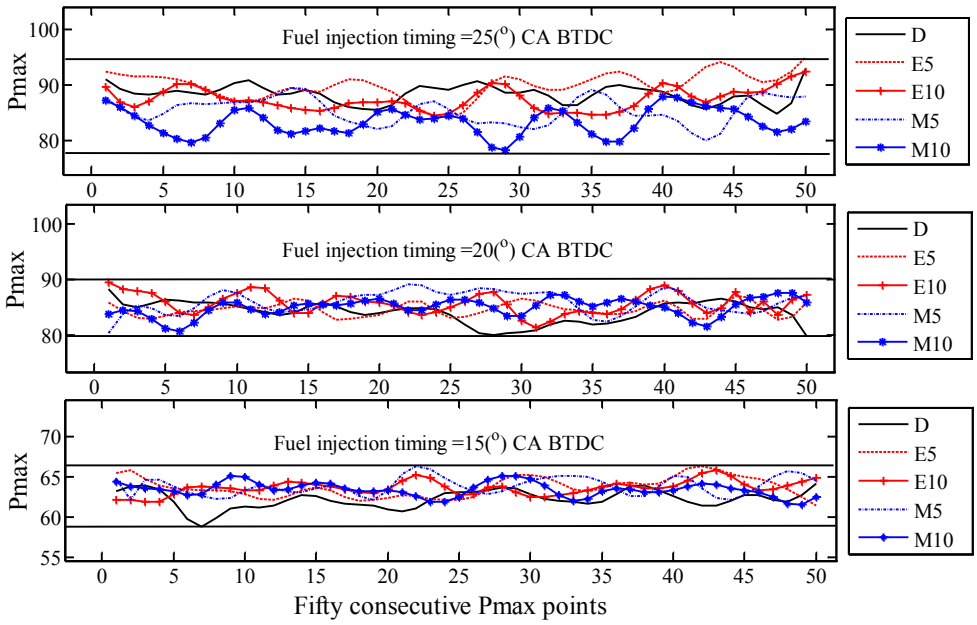


Fig.4 Effects of blends and fuel injection timing on the variation of maximum cylinder gas pressure

5. Conclusion

The paper presented the results of experimental research on the effects of injection timing on the combustion characteristics of an IDI diesel engine using the ethanol and methanol blends with diesel fuel. The following conclusions can be drawn from the current paper:

(1) The P_{max} and premixed combustion rate increased with advanced fuel injection timings for all test fuels.
(2) The location of P_{max} and the start of combustion points occurred early with advanced fuel injection timing.
(3) The ID and TCD decreased with retarded injection timing for all test fuels.
(4) It was determined that the IDs of the blends were longer than that of conventional diesel fuel at originally and advanced injection timings.
(5) An increase in the mass fraction of the methanol and ethanol in the fuel blends generally caused to increase in ID, but it decreased TCD.
(6) The retarding of injection timing decreased the $(dQ/d\theta)_{max}$ and the $(dP/d\theta)_{max}$ for all test fuels.
(7) It was found that the characteristics of $(dQ/d\theta)_{max}$ and $(dP/d\theta)_{max}$ of the blends are higher than that of conventional diesel fuel. These characteristics increased with the increase of methanol and ethanol mass fraction in the fuel blends at original injection timing.
(8) It was observed that the cyclic variability decreased with the retarding fuel injection timings. Also, the maximum cyclic variability was observed with the M10 at the advanced injection timing. The fuel blends used in the current study may replace with

conventional diesel fuel in terms of the combustion characteristics, cycle to cycle variation and smoothness of the engine operation.

References

[1] M. Canakci, C. Sayin, A.N. Ozsezen, and A. Turkcan, Effect of Injection Pressure on the Combustion, Performance, and Emission Characteristics of a Diesel Engine Fueled with Methanol-blended Diesel Fuel, Energy and Fuels 23, 2009, pp.2908-2920.

[2] M. Canakci, C. Sayin, and M. Gumus, Exhaust Emissions and Combustion Characteristics of a Direct Injection (DI) diesel Engine Fuelled with Methanol-Diesel Fuel Blends at Different Injection Timings, Energy and Fuels 22, 2008, pp.3709-3723.

[3] C.Y. Choi, R.D. Reitz, An experimental study on the effects of oxygenated fuel blends and multiple injection strategies on DI diesel engine emissions, Fuel 78, 1999, pp.1303-1317.

[4] L.J. Wang, R.Z. Song, H.B. Zou, S.H. Liu, L.B. Zhou, Study on combustion characteristics of methanol-diesel fuel compression ignition engine, Proc Inst Mech Eng D-J Auto 33, 2008, pp.1314-1323.

[5] Ö. Can, İ. Çelikten, N. Usta, Effects of ethanol addition on performance and emissions of a turbocharged indirect injection Diesel engine running at different injection pressures, Energy conversion and Management 45, 2004, pp.2429-2440.

[6] M. Eyidogan, A.H. Ozsezen, M. Canakci, A. Turkcan, Impact of alcohol-gasoline fuel blends on the performance and combustion characteristics of an SI engine, Fuel 89, 2010, pp.2713-2720.

[7] M.A. Ceviz, F. Yüksel, Effects of ethanol-unleaded gasoline blends on cyclic variability and emissions in an SI engine, Applied Thermal Engineering 25, 2005, pp.917-925.

[8] Z.H. Huang, H.B. Lu, D.M. Jiang, K. Zeng, B. Liu, J.Q. Zhang and X.B. Wang, Combustion characteristics and heat release analysis of a compression ignition engine operating on a diesel/ methanol blend, Proc Inst Mech Eng D-J Auto 218, 2004, pp.1011-1024.

[9] Z.H. Huang, H.B. Lu, D.M. Jiang, K. Zeng, B. Liu, J.Q. Zhang and X.B. Wang, Combustion behaviors of a compression-ignition engine fuelled with diesel/methanol blends under various fuel delivery advance angles, Bioresource Technology 95, 2004, pp.331-341.

[10] C. Yao, C.S. Cheung, Y. Wang, T.L. Chan, S.C. Lee, Effect of Diesel/methanol compound combustion on diesel engine combustion and emissions, Energy Conversion and Management 49, 2008, pp.1696-1704.

[11] L. Xing-cai, Y. Jian-guang, Z. Wu-gao, H. Zhen, Effect of cetane number improver on the heat release rate and emissions of high speed diesel engine fuelled with ethanol-diesel blend fuel, Fuel 83, 2004, pp.2013-2020.

[12] C.D. Rakopoulos, K.A. Antopoulos, D.C. Rakopoulos, Experimental heat release analysis and emissions of a HSDI diesel engine fueled with ethanol-diesel fuel blends, Energy 32, 2007, pp.1791-1808.

[13] A.A. Abdel-Rahman, On the emissions from internal combustion engines: a review, Int. J. Energy Res. 22, 1998, pp.483–513.

Land use, greenhouse gas emissions and fossil fuel substitution of biofuels compared to bioelectricity production for electric cars in Austria

Johannes Schmidt[1, *], Viktoria Gass[1], Erwin Schmid[1]

[1] *Institute for Sustainable Economic Development, University of Natural Resources and Life Sciences, Vienna, Austria*
** Corresponding author. Tel: +43 650 2151579, Fax: +43 1 47654-3692, E-mail: johannes.schmidt@boku.ac.at*

Abstract: Bioenergy is one way of achieving the indicative target of 10% renewable energy outlined in the EU Directive 2009/28/EC. This paper assesses the consequences for land use, greenhouse gas (GHG) emissions and fossil fuel substitution of increasing the use of bioenergy for road transportation. Different technologies, including first and second generation fuels and electric cars fuelled by bio-electricity are assessed in relation to existing bioenergy uses for heat and power production. The paper applies a spatially explicit energy system model that is coupled with a biomass production model to allow estimating impacts of increased biomass utilization for energy production on agriculture and forestry. Uncertainty is explicitly considered with the help of Monte-Carlo simulations of input parameters. Results indicate that second generation fuels perform better with respect to land use than first generation ethanol and that costs are lower. Biodiesel is also a cheap option, although the total potential is limited at a low level due to constraints in feedstock production. Electric vehicle mobility minimizes land use, however, costs are still high and prohibitive. First generation ethanol production is effective in reducing domestic GHG emissions because it does not induce feedstock competition with existing bioenergy uses (i.e. heat and power production). However, land use change is significant.

Keywords: *biofuels, electric cars, e-mobility, 2020 goals, spatially explicit optimization*

1. Introduction

Directive 2009/28/EC requires all member states of the EU to guarantee a share of 10% of renewable fuels in transportation by 2020. The target may be reached by various measures, including an increase in the share of biofuels and an increase in the share of renewably produced electricity in the transportation sector. However, since the large scale introduction of biofuels in the US and Europe an extensive discussion has evolved because the large land requirements were identified as cause for direct and indirect greenhouse gas (GHG) emissions [1], [2] and as the driver for increasing competition between food and fuels [3], [4]. In Austria, bioenergy has played traditionally an important role. It provided around 8% of the primary energy demand in 2006, mainly for heating purposes [5]. Other uses of bioenergy developed in recent years, include biofuel and power production. Austria has complied with the 5.75% indicative EU biofuel target since late 2008 and used around 4.00 TWh of biodiesel and 0.60 TWh of ethanol in 2008 [6]. A further increase of the supply of biofuels will be difficult to achieve, particularly if only domestic biomass supply is considered. However, new technologies are emerging that aim to increase biofuel productivity and diversify feedstock supply. Second generation biofuels that may use ligno-cellulosic feedstock for fuel production are regarded as a sustainable alternative to first generation biofuels which are mainly produced from food and feed crops [2], [7]. A technological alternative is electric cars. Technical and economical barriers currently prevent the large scale introduction of electric cars, however, future potentials are considered significant [8], [9]. Electric cars will only contribute to renewable energy targets if the electricity for cars is produced in a renewable manner. Biomass is one possible source for this purpose. An existing study estimates [10] that the utilization of biomass resources for electricity generation and subsequent utilization in electric cars is a far more effective way of using limited land resources for transportation than the conversion of food and feed crops to first generation ethanol. However, the assessment relied merely on technical details without considering economics and alternative uses of biomass in

the energy sector – e.g. for heating. This paper contributes to research by applying a spatially explicit agricultural-bioenergy-system model to evaluate several technological options for the transportation sector, including first and second generation fuels and electric cars, with respect to land use, GHG emissions and fossil fuel substitution. The techno-economic characteristics of future biofuel production as well as of electric cars are not well known yet. Also, high uncertainty is attached to future price energy scenarios. We therefore apply a Monte-Carlo simulation of input parameters to explicitly include uncertainty in the modeling process.

2. Methodology

2.1. Model and Model Boundaries

A spatially explicit, techno-economic mixed integer program is developed and applied to assess the costs, land use and GHG emissions of different bioenergy conversion routes. The model minimizes the costs of supplying Austria with transportation fuels, heat and electricity from either bioenergy or fossil fuels. It is static and simulates one year of operation. The current model version considers domestic biomass supply and energy demand only and does not allow imports and exports of biomass or bioenergy commodities. The model determines which bioenergy plants of a specific size and specific location shall be built and which demand regions are supplied with bioenergy and/or with fossil fuels. Each plant produces various energy commodities, e.g. the heat produced in a combined heat and power (CHP) may be delivered to district heating networks (Figure 1). By-products of biofuel plants are sold as animal feed. Biomass supply curves endogenously determine the price of feedstock from forestry and agriculture, while prices of fossil fuels and energy demand are defined exogenously. Taxes currently applied to both fossil and bioenergy fuels are not included in the model.

2.2. Technologies

We assess several bioenergy technologies which are able to replace fossil fuels in the transportation sector along with technologies that convert biomass to heat and power. First generation biofuels are classified into ethanol produced from fermentation of starchy and sugar crops (e.g. wheat and corn) and biodiesel which is produced from vegetable oil derived

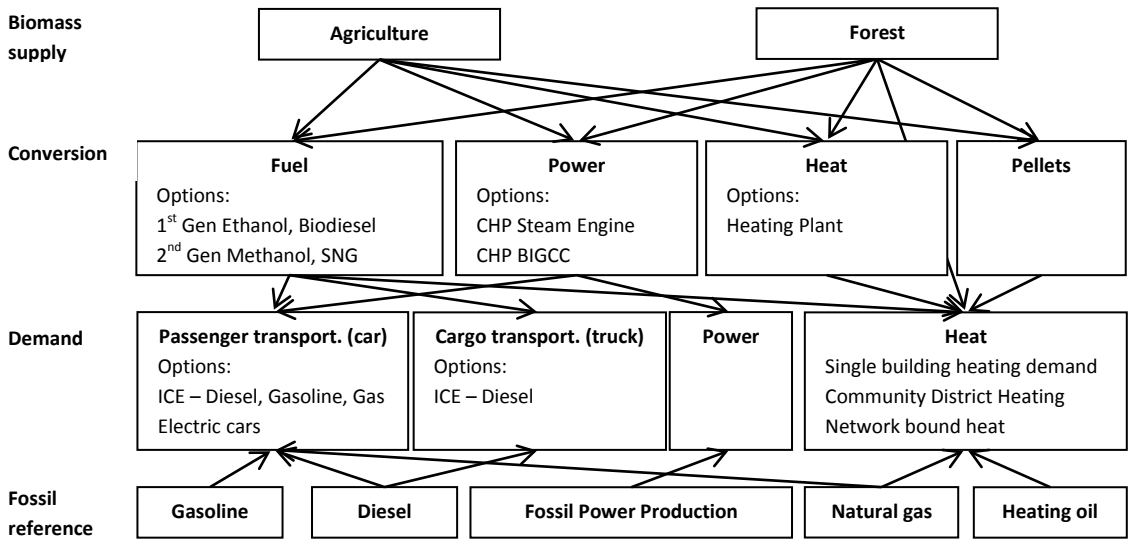


Figure 1: Diagram of the mixed integer programming model.

from oil crops (e.g. sunflower and rapeseed). Both technologies are commercially available and are currently used for the production of biofuels in Austria**.** Ethanol is blended with gasoline. A blend of 5% ethanol and 95% gasoline is considered safe to be used in all cars,

while all cars sold currently on the market are also able to handle a blend of 10% of ethanol. Similar limitations apply to biodiesel [11]. Second Generation biofuels are able to use cellulosic feedstock and even waste for the production of biofuels. There are two major technological options [7]. The biomass can be gasified and subsequently upgraded to liquid transportation fuels such as methanol or synthetic natural gas (SNG) which can also be used as transportation fuel. The second option is the hydrolysis of cellulose to sugars that are fermented to ethanol afterwards. We assess gasification only as it is estimated to be economically more viable than hydrolysis with fermentation [12], [7]. Second generation production technologies are currently under research and first pre-commercial installations are being built. US legislation requires 572 TWh of yearly cellulosic biofuel production until 2022 [13], therefore a rapid increase in the construction of second generation facilities can be expected. Current cars cannot run solely on methanol and the amount of methanol that may be blended to gasoline is, similar to ethanol, limited. SNG requires significant modifications to the car, including the installation of a gas tank. Electric cars are currently globally under research, however, costs and ranges of batteries are major economic and technical obstacles to full implementation of the technology. Ranges of above 150 km are currently only achieved at very high costs [9]. Also, electric cars need the large scale deployment of charging stations. Metering of power and billing still has to be developed. The model considers investment costs for electric cars. Costs associated with additional infrastructure necessary for electric cars are not included. With respect to power production, the model allows two technologies: steam engines and biomass integrated gasification combined cycle (BIGCC) plants. While steam engines are well established in Austria and the installed capacity exceeded 300 MW in 2007 [5], BIGCC is a technology that is still under research. It allows higher electrical conversion efficiencies than steam engines but capital costs are also significantly higher. We assume that power can be either used to fuel electric cars or that it is simply sold on the electricity market at a fixed price. Heating technologies modelled include fuel wood furnaces, pellet furnaces and heating plants for district heating networks.

2.2.1. Total Cost of Ownership – Cars

We use the concept of total cost of ownership (*tco*) to assign different costs to different cars in the model. Costs for fuels are endogenously determined by the model and are therefore not included in the calculations of *tco*. The *tco* per km is described by equations (1)-(3):

$$tco = \frac{C\frac{i(1+i)^t}{(1+i)^t-1}+B}{km} + om \qquad (1)$$

$$t = \min\left(\frac{maxKm}{km}, 10\right) \qquad (2)$$

$$B = \frac{i(1+i)^{tb}}{(1+i)^{t}b-1}\sum_{tb\in y}\frac{bc}{(1+i)^{t'}} \qquad (3)$$

The *tco* is determined by the annuity of capital costs *C* of the car, assuming an interest rate *i* and a lifetime *t*. For electric cars, the battery cost *B* is additionally considered as explained below. Total necessary yearly investment costs are divided by the kilometres *km* driven annualy. Additionally, operation & management costs per km of *om* are assumed. These costs are assumed to be lower for electric cars because maintenance of the electric motor is less complex than for an internal combustion engine (ICE) [9]. The lifetime of the car is limited to ten years, however, if the car is driven a lot (i.e. more than *maxKm*), the lifetime is further reduced as indicated by equation (2). The lifetime of a battery is significantly less than that of the carriage. A change of the battery within the lifetime is therefore probable and is modelled

by equation (3): the annuity of battery costs is derived by adding up the discounted battery costs over the whole life time, assuming that one battery costs *bc*. The battery is changed in year *y* when the driven kilometres since the last change exceed the lifetime of the battery. The *tco* depends significantly on the kilometres driven each year. A higher amount of kilometres implies lower specific capital costs per km. We therefore estimate ten classes of annual car utilization based on data provided by ÖAMTC. ÖAMTC, the biggest Austrian Automobile Association, checks approximately 10% of all cars for their technical liability each year. The total driven kilometers and the year of the first registration of the car are collected in the examination of the cars. An approximate estimate of the yearly driven kilometers can be derived from this data. We classified the cars by the annual driven kilometers into ten classes (0 km - 10,000 km, 10,001 km - 20,000 km, …, 90,000 km – 100,000 km). For each class, the mean of the yearly driven kilometers by car and the mean of the sum of driven kilometers by all cars in the class are determined. The sum of driven kilometers is linearly extrapolated from the ÖAMTC data with data of total Austrian car ownership from Statistik-Austria to allow an estimate for whole Austria as ÖAMTC data only covers around 10% of all registered cars.

2.3. Demand

We estimate current transportation demand from the ÖAMTC data and assume that the demand for transportation remains constant until 2020. We assume a total of 60 billion annual kilometres for personal transportation and total of 24 billion tonne kilometres for cargo transportation by truck. Although transportation fuel consumption has historically seen significant increases in the last years, the increase was significantly caused by “tank tourism” due to lower fuel taxes in Austria. We exclude demand from “tank tourism” from our analysis and also assume that public transportation will take a higher share of the overall transportation supply, thus allowing that road transportation remains constant. While the model allocates biomass resources to various conversion routes depending on energy prices and production costs, the demand for biomass heating is assumed to not fall under 17 TWh in the simulations. This is a possible decline of 5 TWh from current consumption levels. Setting a lower bound for biomass consumption for heating is reasonable because adjustment of individual heating devices to new economic conditions generally takes a lot of time.

2.4. Uncertainty

Most of the parameters in the study are of high uncertainty. Uncertainties on the performance and costs of various technologies as well as uncertainty about future energy prices are high. We explicitly address this issue by performing Monte-Carlo simulations of the MIP model and conducting an extensive sensitivity analysis. We first define plausible ranges for the uncertain parameters from a literature research and assume that the parameters are distributed uniformly within that range. For energy and CO_2 prices, correlation between the prices of oil, gas, gasoline and CO_2 are determined from historical spot prices**.** The input data for the Monte-Carlo simulation is generated by performing a Latin Hypercube Sampling procedure and combining it with the Iman-Conover method to guarantee correlation of correlated parameters in the procedure [14]. Latin Hypercube Sampling is used to guarantee that the whole parameter range is covered in the Monte-Carlo simulations. Results are given in form of probability distributions and a stepwise regression analysis is performed to examine the sensitivity of results to input parameters. The assumption on the distribution of the most important parameters is reported in Table 1. Further parameters modelled stochastically are biomass costs, conversion efficiencies and investment costs of bioenergy plants.

Table 1: Main model parameters and uncertainty ranges

	Lower Bound	Upper Bound
Price of oil (€ MWh^{-1})	40	60
Price of gas (€ MWh^{-1})	30	50
Price of gasoline (€ MWh^{-1})	42	62
Price of electricity (€ MWh^{-1})	54	74
Price of carbon (€ MWh^{-1} tCO_2^{-1})	21	55
Battery costs (€)	4,000	6,500
Replacement distance battery (km)	70,000	90,000
Investment costs electric cars (w/o battery) (€)	14,000	16,500
Investment costs gasoline cars (€)	16,500	16,500
Investment costs diesel cars (€)	17,000	17,000
Investment costs gas cars (€)	17,500	17,500
O&M costs electric car (€ km^{-1})	0.02	0.025
Conversion efficiency car – Gasoline (km MWh_{fuel}^{-1})	2,000	2,200
Conversion efficiency car – Diesel (km MWh_{fuel}^{-1})	2,250	2,450
Conversion efficiency electric car (km MWh_{elec}^{-1})	5,600	7,000

2.5. Scenarios

We model one baseline scenario, that assumes no policy intervention at all, and 7 policy scenarios. Three of the scenarios assume that 5% (*S5*), 10% (*S10*) and 15% (*S15*) of the transportation sector are supplied by bioenergy, allowing all technologies to be selected by the model. The other four scenarios examine the impact of a 10% target of renewable transportation fuels, if only single technologies (i.e. ethanol (*eth*), methanol (*met*), sng (*sng*), electric mobility (*emo*)) are allowed. Biodiesel is not modelled in these scenarios because domestic feedstock production is too low to supply 10% of the transportation sector with biofuels.

3. Results

3.1. Technologies and fuel utilization

The first three scenarios allow free choice of technologies. Biodiesel and methanol supply the biofuels in these scenarios. Biodiesel is however limited at around 0.5 TWh due to restrictions in feedstock supply of oil-crops. Second generation methanol is the supplement to biodiesel to complete the full target. E-Mobility plays a role in the first three scenarios - however, variation is very high and the contribution is significantly lower than that of methanol. Ethanol and SNG are not selected in the first three scenarios. These results indicate that methanol production can be considered superior to ethanol in terms of costs – although the variation of results is generally high, the dominance of methanol over ethanol is stable. Competing bioenergy technologies (i.e. heating and power production) are mainly reduced in *S15, met* and *SNG*. This is due to the high demands for woody biomass for biofuel production which increases prices for the feedstock and therefore makes production of power and heat partly unprofitable. The ethanol scenario has less influence on the woody biomass market as ethanol feedstock competes with food and feed crops. Biodiesel is mainly used in the freight sector where it substitutes diesel. Ethanol and methanol are used for personal transportation in driving classes with low annual distances because fixed capital costs contribute more to the total costs of transportation in those classes than the distance dependent fuel costs. Higher classes with higher annual driving distances are more likely to be supplied by electric cars where the influence of the high capital costs of the car and the battery decrease and the fuel costs become more important.

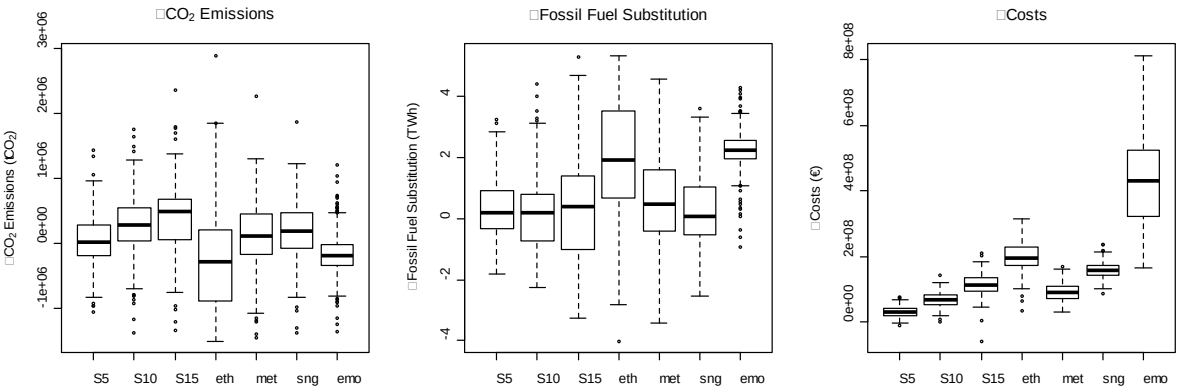


Fig. 2: Differences in CO_2-Emissions, Fossil Fuel Substitution and Costs between the baseline and the biofuel scenarios.

3.2. CO_2 Emissions, Fossil Fuel Substitution and Costs

Figure 2 shows CO_2 emissions, fossil fuel substitution and costs calculated as the difference from the baseline scenario. A significant reduction in CO_2 emissions and an increase in fossil fuel substitution are achieved by the *eth* and the *emo* scenario. These two scenarios also have highest costs. The variance of costs is highest in *emo* due to the large uncertainties in the development of the costs of electric vehicles. However, the model only considers domestic GHG emissions while effects of indirect land use change on GHG emissions are not modeled.

3.3. Land use

While the *eth* policy substitutes a lot of fossil fuels, the land use effects are also substantial in comparison to the other policy scenarios (See Figure 3). Up to 200,000 ha of agricultural land are converted to energy crop production while all other scenarios stay well below 50,000 ha. This implies that food and feed production is reduced significantly in the *eth* scenario while all other policies have rather low impacts on the production of other agricultural products. There are two reasons for this: first, productivity is higher for second generation fuels and for electric mobility due to higher total conversion efficiencies (see Figure 3). Second, these technologies rely on lignocellulose resources that may come from additional forest harvesting or that may otherwise be used for power and heat production (see Figure 3, bottom-right). There are also important differences between the *S10*, *met*, *sng* and *emo* scenarios. Combining biodiesel and methanol for the biofuel goals as in *S10* reduces land use change in comparison to the methanol only scenario. Biodiesel therefore plays a small, but important role in the technological portfolio. Figure 3 shows that *SNG* is more efficient in converting biomass than methanol. Electric mobility has by far the lowest impact on land use change and on additional forest wood utilization.

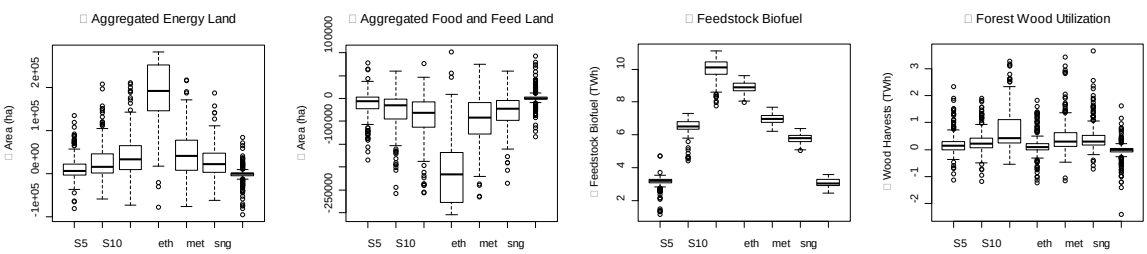


Fig. 3: Differences in Land Use, Feedstock Utilization and Forest Wood utilization between the baseline and policy scenarios.

3.4. Sensitivity Analysis

Table 2 show the results of the sensitivity analysis performed on the results of the *S15* scenario. We checked for the influence of parameters on the deployment of electric mobility to show which factors mainly influence the competition between second generation fuels and electric mobility by performing a regression of the input parameters on the output variables (a stepwise regression procedure is used). The regression coefficients are normalized. The most important input parameters regard the cost for the electric car (i.e. battery costs, investment costs, O&M). The carbon price and the kilometers until replacement of battery also prove to significantly influence the results while the gasoline price does not show significant influence on results.

4. Discussion

Results of our study are in line with other studies that estimate lower land use for bio-electric-cars than for biofuel production [10]. They are also in line with studies that come to the conclusion that battery replacement costs are currently the biggest economic barrier to the large scale introduction of electric mobility in the transportation sector [8], [9]. However, there are additional barriers to electro-mobility that were not modelled within this study: the change from cars that are refuelled at gas stations in very short time to cars that need hours of recharging and that have a comparably low driving range probably plays a more important role than sole considerations of the *tco*. The model results indicate that drivers who use their car a lot are more likely to choose electric cars than those with low car utilization because of lower fuel costs. However, technical reasons may impede the utilization of electric cars for those drivers: the low range and the high recharging times may render electric cars impractical for them. With respect to economics, renewable electricity production from wind or small water power plants may produce electricity at much more competitive costs than biomass powered thermal plants. Therefore, electric cars may be more competitive than stated in this study due to lower fuel costs from renewables. The GHG emission effects of biofuel policies have to be considered in conjunction with the land use change that is caused by the expansion of biofuel production. The GHG emissions stated in this paper do not include indirect or leakage effects of the policies. However, it can be clearly stated that fuelling electric cars with electricity produced from biomass induces by far the least change of land use and can therefore be considered to also minimize leakage effects.

*Table 2: Results of sensitivity analysis. Confidence levels: *** 0.999, ** 0.99 and * 0.95*

	Coefficient	
Amount of electric mobility (R^2 0.49)		
Battery Costs	-0.54	***
Investment costs electric car	-0.28	***
O&M costs electric car	-0.12	*
Gasoline price	0.08	
Kilometers until replacement of battery	0.15	**
Carbon price	0.17	**

5. Conclusions

Second generation biofuels have less impact on land use than first generation ethanol due to two reasons: yields of biofuel per hectare are higher for agricultural land and the feedstock may additionally come from forests. Biodiesel has high yields per hectare, but the total domestic potential is limited at a low level. The lowest land use is implied by the utilization of

electric cars, which, at current technological standards, are still very costly in comparison to cars fuelled by liquid fuels. With respect to policies for promoting second generation biofuel production, one has to consider that investments in second generation biofuel production will have a long-term effect on the utilization of biomass resources. The results of the study indicate, however, that the gains in efficiency in relation to first generation fuels are relatively low while significant efficiency increases can only be expected when developing a transportation system based on electricity. A large scale introduction of second generation biofuels has to be considered very carefully therefore and in the light of a possible total restructuring of the transportation sector within the next 20 to 30 years.

References

[1] T. Searchinger et al., "Use of U.S. croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change," *Science*, vol. 319, no. 5867, pp. 1238-1240, 2008.

[2] P. Havlík et al., "Global land-use implications of first and second generation biofuel targets," *Energy Policy*, p. doi:10.1016/j.enpol.2010.03.030, 2010.

[3] B. A. Bryan, D. King, and E. Wang, "Biofuels agriculture: landscape-scale trade-offs between fuel, economics, carbon, energy, food, and fiber," *GCB Bioenergy*, vol. 2, no. 6, pp. 330-345, 2010.

[4] P. Dauvergne and K. J. Neville, "Forests, food, and fuel in the tropics: the uneven social and ecological consequences of the emerging political economy of biofuels," *Journal of Peasant Studies*, vol. 37, no. 4, p. 631, 2010.

[5] L. Kranzl and R. Haas, *Strategies for the optimal development of biomass potentials in Austria until the year 2050 aiming at a maximal reduction of green house gas emissions (Strategien zur optimalen Erschließung der Biomassepotenziale in Österreich bis zum Jahr 2050 mit dem Ziel einer maximalen Reduktion an Treibhausgasemissionen)*. Energy Economics Group, University of Technology Vienna, 2008.

[6] R. Winter, *Biokraftstoffe im Verkehrssektor in Österreich 2008 (Biofuels in the transportation sector in Austria 2008)*. Umweltbundesamt, 2010.

[7] J. Lange, "Lignocellulose conversion: an introduction to chemistry, process and economics," *Biofuels, Bioproducts and Biorefining*, vol. 1, no. 1, pp. 39-48, 2007.

[8] C. Sandy Thomas, "Transportation options in a carbon-constrained world: Hybrids, plug-in hybrids, biofuels, fuel cell electric vehicles, and battery electric vehicles," *International Journal of Hydrogen Energy*, vol. 34, no. 23, pp. 9279-9296, 2009.

[9] C. Thiel, A. Perujo, and A. Mercier, "Cost and CO2 aspects of future vehicle options in Europe under new energy policy scenarios," *Energy Policy*, vol. 38, no. 11, 2010.

[10] J. E. Campbell, D. B. Lobell, and C. B. Field, "Greater Transportation Energy and GHG Offsets from Bioelectricity Than Ethanol," *Science*, p. 1168885, 2009.

[11] O. van Vliet, M. van den Broek, W. Turkenburg, and A. Faaij, "Combining hybrid cars and synthetic fuels with electricity generation and carbon capture and storage," *Energy Policy*, vol. 31, no. 1, 2011.

[12] S. Bram, J. De Ruyck, and D. Lavric, "Using biomass: A system perturbation analysis," *Applied Energy*, vol. 86, no. 2, pp. 194-201, 2009.

[13] Environmental Protection Agency, *Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule*. 2010.

[14] A. Saltelli and MAT, *Sensitivity Analysis*. Chichester [u.a.]: Wiley, 2000.

Technological challenges for alternative fuels technologies in the EU. A well-to-Tank assessment and scenarios until 2030 considering technology learning

Felipe Toro[1*], Martin Wietschel[2]

[1] *IREES GmbH, Schoenfeldstraße 8, 76131 Karlsruhe, Germany*
[2] *Fraunhofer Institute for Systems and Innovation Research, Karlsruhe, Germany*
**Felipe Toro. Tel: +49-721-915263621, Fax:+49-721-915263611, email: f.toro@irees.de*

Abstract: The initial step of this analysis corresponds to the evaluation of the current state of the art (SoA) for various alternative fuels (AFs) and alternative sustainable automotive technologies (ASATs) across Europe, taking into account their detailed energetic, environmental and economic variables. The method to assess economic and environmental performance of AFs and ASATs corresponds to a well-to-tank (WTT) and tank-to-wheel (TTW) assessment complemented by scenarios until 2030, with projections of reference and high prices of major input variables of analysis. This analysis determines short and long term economic performance taking into account technology learning. 2nd generation biofuels offer potentials for meeting future fuel-energy demand, and are currently supported by main governments and programs. Initial results of this study also indicate that second generation biofuels offer promising solutions in terms of environmental performance but production costs, conversion efficiencies and by-products are major challenges that can influence the overall economic performance considerably. In addition, price volatilities for first generation biofuels feedstock play a major role on the competitiveness and economic performance of these fuels.

Keywords: *Sustainable transport, Low carbon fuels, Alternative fuels, Mobility technologies, Economic assessment*

1. Introduction

Biofuels and alternative fuels (AFs) have emerged strongly since last one decade as sustainable alternatives for the reduction of fossil fuel energy demand and emissions in the transport sector. Various AF production options include 1st generation biofuels (biodiesel and bioethanol) obtained from well established fermentation, oil extraction and trans-esterification processes, as well as emerging 2nd generation biofuels via BTL, gasification, CTL and other processes. Currently, several technological challenges and bottlenecks exist in different AF production options at different levels across the whole supply chain. Biomass supply constraints, inefficient and capital intensive production processes, fuel transportation and supply, onboard usage related problems and many others are such challenges that affect the success and proliferation of these AFs. The expected economic and environmental performance of these alternatives require not only a clear understanding of the current state of the art, but also a comparison between various alternatives along the complete supply chain as "well-to-tank" and "tank-to-wheel" analysis. Within this study, scenarios for the future development of the most important input variables in different AF production pathways have been defined with feedstock costs and production-scale effect variations that influence the overall economic performance.

2. Methods and modelling structure

The current state of the art and developments of AFs and ASATs have been studied by various authors in different projects and studies. In this study, the characterization of technologies along the whole technology cycle included an extensive literature review including research papers, studies, industrial information, etc. from 2003 until 2010, as well as expert's interviews and assessments in order to screen the state of development of alternative fuel technologies along the technology cycle curve (S-Curve) [1,4]. State of the art updates and projections until 2030 were collected for 26 different AFs pathways through

techno-economic databases including information on biomass feedstock requirements, production process input characterizations (inputs, quantities, efficiencies, costs, emissions) and other techno-economic and techno-environmental parameters. The main formulas and assessments used in this study include the annual cost of capital (ACC):

$$\mathbf{ACC} = \frac{IR}{1-\left(\frac{1}{(1+IR)^{Te}}\right)} * Ti * 1 - \left(\frac{1}{(1+IR)^{Te}}\right) * \left(\left(\frac{Tt-Te}{Tt}\right)\right)$$

Ti corresponds to total investments, *Te* to economic lifetime and *Tt* to technical lifetime while IR is the interest rate. For this particular research it was established as 8% for all AF technologies; however it could be higher for 2nd generation and other unavailable technologies due to risks related. Total costs have been estimated as the sum of capital costs and O&M costs which were either found in existing examples or estimated based on the technical configuration of plants and assuming operating conditions (e.g. annual operation hours) by taking into account maintenance due to associated risks of new technologies [1,2,4].

2.1. Technology Learning

Technology learning is projected in the future development of specific investment costs based on the cumulative number of plants in relationship to an assumed progression ratio [4,5,6,7,8]. The currently existing plants especially for 2nd generation AF technologies are either very new or with short commercial history thus making it difficult to have reliable data and technology experience. Therefore, this parameter has been built as an adjustable progress ratio (***Pr***) as experienced in case of other industries like aviation, machinery, wind mills etc. and it reflects a maximum of 10 to 30% progress ratio differentiated in small and large scale plants. The following equation indicates the specific investment costs ***(SIC)*** taking into consideration total investments ***(Ti)*** and installed capacities ***(Ic).*** The indicator ***TPI*** corresponds to a technological progress indicator based on the assumed cumulative number of plants as function of time within 5 years periods.

$$\mathbf{SIC} = \frac{\mathbf{Ti}}{\mathbf{Ic}} * \mathbf{TPI} * \left(\frac{\mathbf{Log\ Pr}}{\mathbf{Log\ 2}}\right)$$

2.2. Well to Tank (WTT) and Tank to Wheel (TTW) assessment

The WTT assessment in this study relates to the amount of energy expended and the associated GHG emitted in various steps involved in production and delivery of the fuel. The economic assessment of the pathways considers the scale of production and revenue generated through by-products and other associated production costs. Depending on inputs, WTT economic performance [c€/kWh] and CO_2 emissions have been calculated with the steps involved in producing one kWh of alternative fuel and the corresponding inputs (like electricity, heat, fuel and biomass feedstock) as well as the corresponding emissions factors for each particular input variable. This detailed WTT analysis of the pathway(s) describes various processes involved in cultivation of the feedstock until the distribution of finished fuel at the filling station. The TTW assessment accounts for the energy expended and the associated GHG emitted by the fuel and vehicle technology combinations. In this assessment, the internal combustion engine vehicles were considered to propel with pure biofuel (such as ETBE, FT-diesel) or blended with conventional fossil fuel (E85, B5) [3,4,11]. Complete WTW CO2 emissions were assessed by combining the emission generated during the fuel production pathways WTT [gCO2eq/km] and TTW [gCO2eq/km] emissions generated by combustion of fuel at the level of vehicle. The data that WTW assessment includes are the WTT emitted GHG and expended energy (i.e. excluding the energy content of the fuel itself)

per unit energy content of the fuel [MJf/100 km] and the TTW energy consumed by the vehicle per unit of distance covered.

3. Assumptions

3.1. WTT – Technology Pathways

Biofuel technology pathways were pre-selected by carrying out a pathway analysis based on the evaluation of costs and emissions performance at various stages of production until delivering biofuel at the filling stations. Year 2010 was selected for comparison between conventional and advanced biofuels, as AFs were to have a commercial start up onwards. In the respect of WTT assessment, 26 biofuel pathways were analyzed in this research and they are described in detail below.

Biodiesel pathways stated include rapeseed and sunflower grain cultivation and transportation to the extraction of oil in small scale (SS) or large scale (LS) extraction plants, production of biodiesel in small scale (SS) or large scale (LS) plants, distribution by trucks and storage at filling station (FS). The consideration of by-products for the assessment result in *8 pathways* for the case of biodiesel as indicated below.

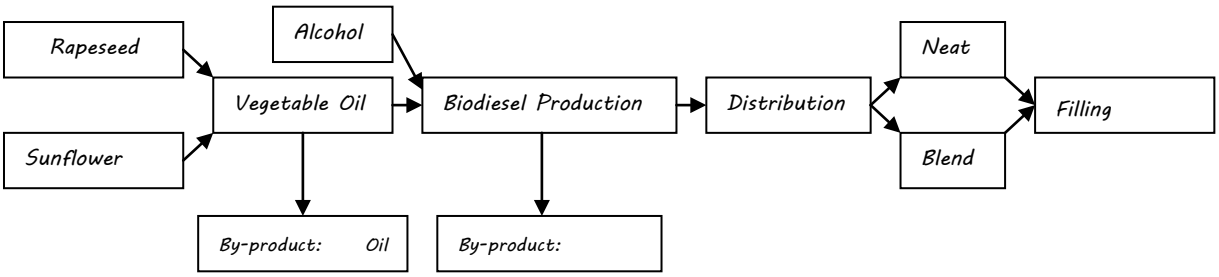


Figure 1: Biodiesel WTT pathways
Source: [1,2]

For bioethanol, *12 WTT pathways* were analysed for both conventional (1st generation) and advanced options (2nd generation) considering biomass production and transport, bioethanol production and distribution until the filling station (FS). Bioethanol production is modelled in small scale (SS) and large scale (LS) plants and the revenues generated from by-products were considered for the assessment (separate pathways for by-products revenues). For lignocellulosic ethanol, by-products have been considered along all the pathways but the differences lie among the feedstock used.

The six BTL Pathways (Figure 3*)* take into account the scale of production plants (small scale, medium scale and large scale) as well as the use of by-products (electricity, heat) however, the differences lie on the biomass pre-treatment techniques using either pyrolysis oil or woodchips pre-gasification in small, medium and large scale F-T Diesel production plants. Power generation data is currently based on demonstration or CHP standard configurations on efficiency and costs. The use of power generation by BTL has the highest contribution to reduce emissions and increase competitiveness.

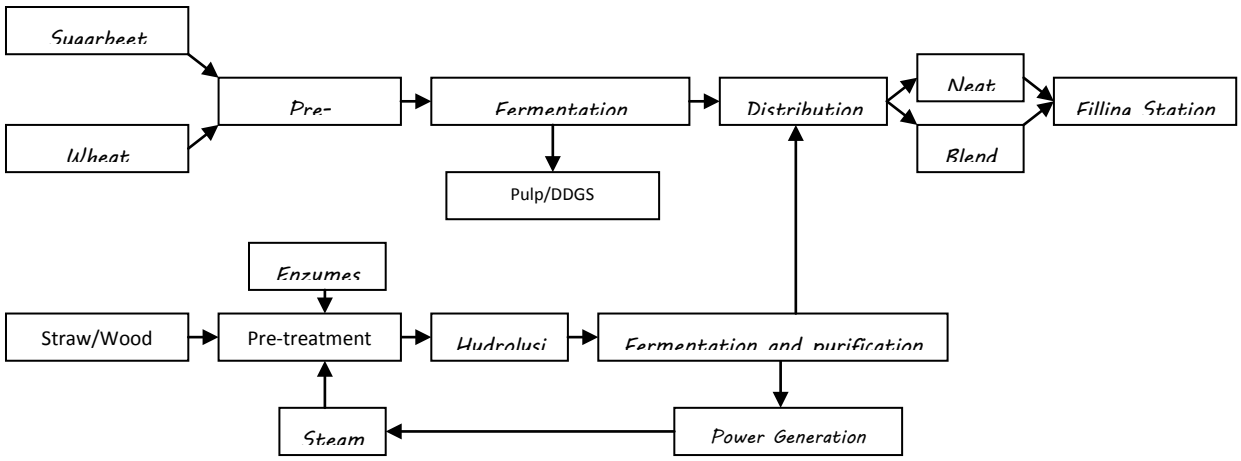


Figure 2: Bioethanol WTT pathways
Source: [1,2]

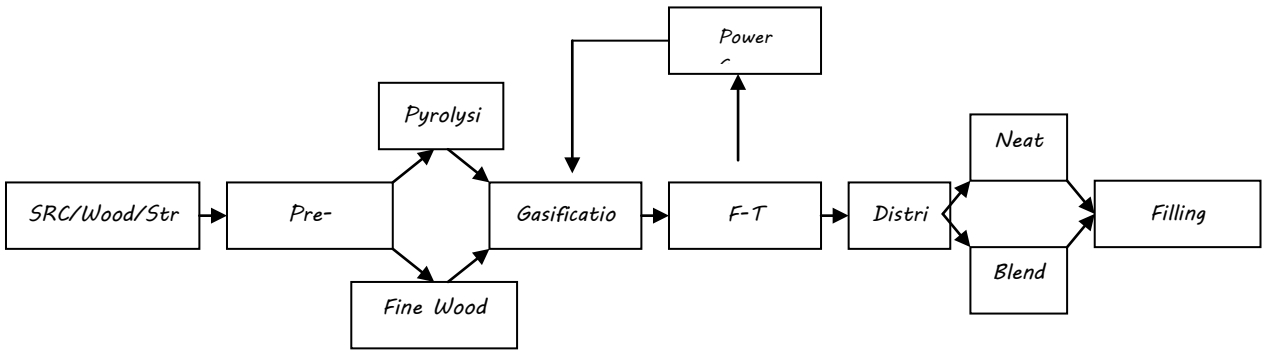


Figure 3: Biomass-to-Liquids Pathways
Source: [1,2]

3.2. Scenarios definition

One *reference and* one *high price* scenarios are defined in this research including the projection of the most important drivers for the production development of alternative fuels AF (e.g. feedstock prices, input prices, co-products). This is a new approach combining not only a mere techno-economic characterization of several technologies but simulating future economic performance under changing the most important parameters dynamically in 5 years steps until 2030. The scenario I (reference) projects until 2030 the most important input materials for alternative fuels production such as biomass feedstock prices, electricity, heat and fuels. The projection reflects conditions before the economic crisis for scenario I considered as a *reference* projection. Scenario II reflects a high prices environment for the same parameters.

With respect to the technology learning the progress ratio, shown as indexed changes in percentage below, reflects enhanced learning as cumulative capacities and production are achieved (scenario II). However, the technology learning projections partially simulate a normal and enhanced learning conditions for AF technologies not directly correlated with the price development of scenario I and II. The values for the major inputs projections for both scenarios and progress ratios are shown in Figure 4 in [c/kWh] and Figure 2 in [%].The projections have been cross checked with experts' assessments and the review of several studies on feedstock prices since 2004 until 2010 [1,2,4,9,10,11]; however, Figure 4 projections assumptions have been made based in correlation with the development of the

projected diesel prices for both reference and high price environments. Two progress ratios changes for technology learning are assumed for modelling technology learning possibilities as shown in Figure 5.

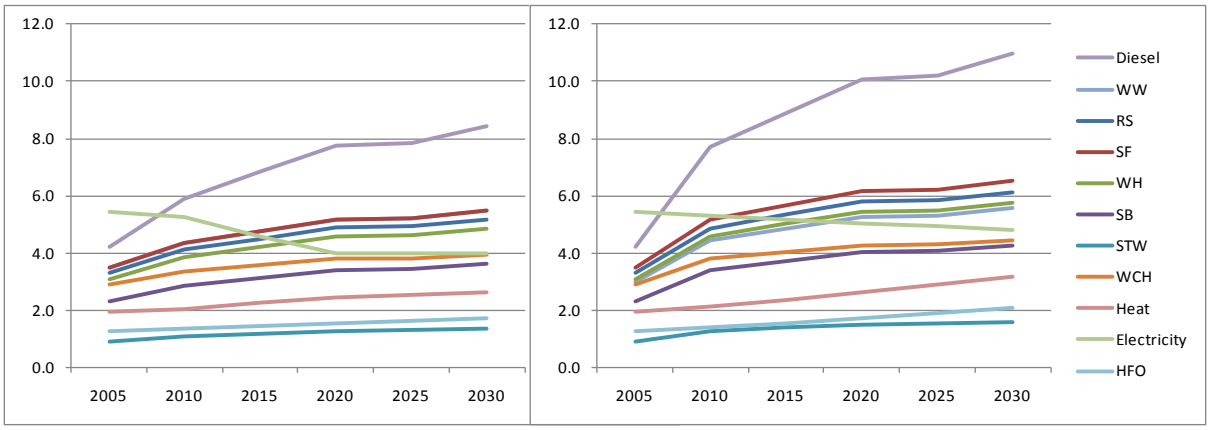


Figure 4: Assumed price changes for AF technologies inputs for scenario I (left) and II (right) until 2030 – [c/kWh]

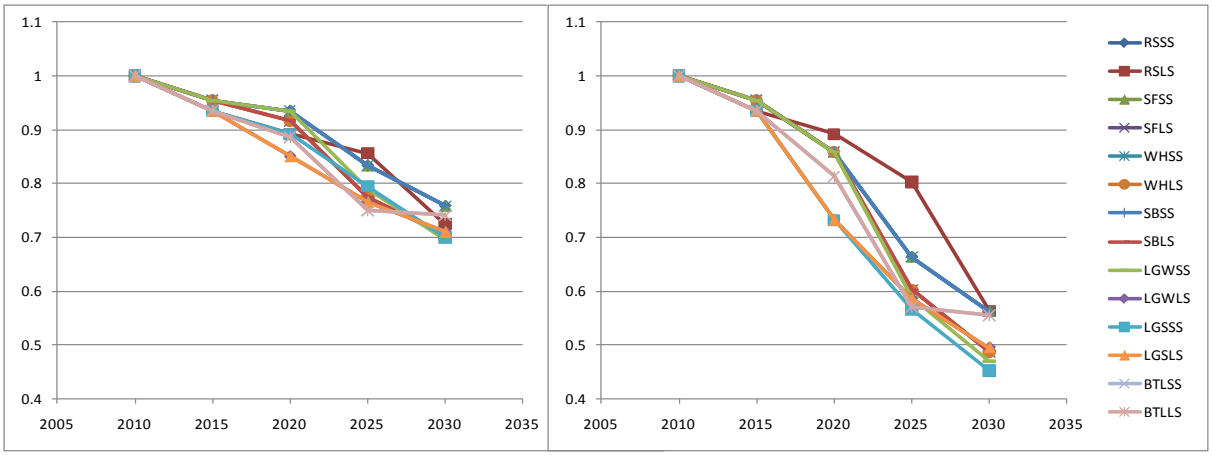


Figure 5: Changes in progress ratios (PR) for AF technologies (large and small scales) for scenario I (left) and II (right) until 2030- [% - index year 2010]

The scenario assumptions should be carefully interpreted as they have strong interaction with other variables (e.g. yields, climate conditions, dietary changes, etc) not directly modelled in the present construct. These scenarios have been defined for all pre-selected pathways, in particular with their inputs such as feedstock for 1st and 2nd generation biofuels, heat, electricity or heavy fuel oil (HFO) among others. In addition, a further assumption is done for technology learning with lower or higher progress ratios in 5 years steps differentiated for small and large scale units.

4. Results and discussion

Results of WTT assessment are illustrated for biodiesel and bioethanol pathways in Figure 6 and Figure 7. BTL results are also available but omitted in graph form due to space limitation. Both figures illustrate the economic performance changes of AFs pathways for both the *reference and high price* scenarios as well as due to the considerations in enhanced technology learning progress ratios for the years 2010 until 2030 in 5 years steps. The number below the graphs corresponds to the number assigned to the pathway for each particular

alternative fuel analysed. Pathway 1[1] (2010) and 27 (2030) for example are identical in configuration but 27 reflects 2030 results. Production economic performance increases 17% in scenario *reference* while almost 20% in scenario II compared to 2010 values. A 2.5% annual increase of rapeseed prices until 2030 (high prices) increases in 16% the costs for oil extraction and biodiesel production when compared to the *reference scenario*. The learning effects are observed in the right side graphs where pathway number 27 reduces its cost performance in further 2% by learning with high progress (experience) ratios of 75% for large scale plants and 80% for small scale plants.

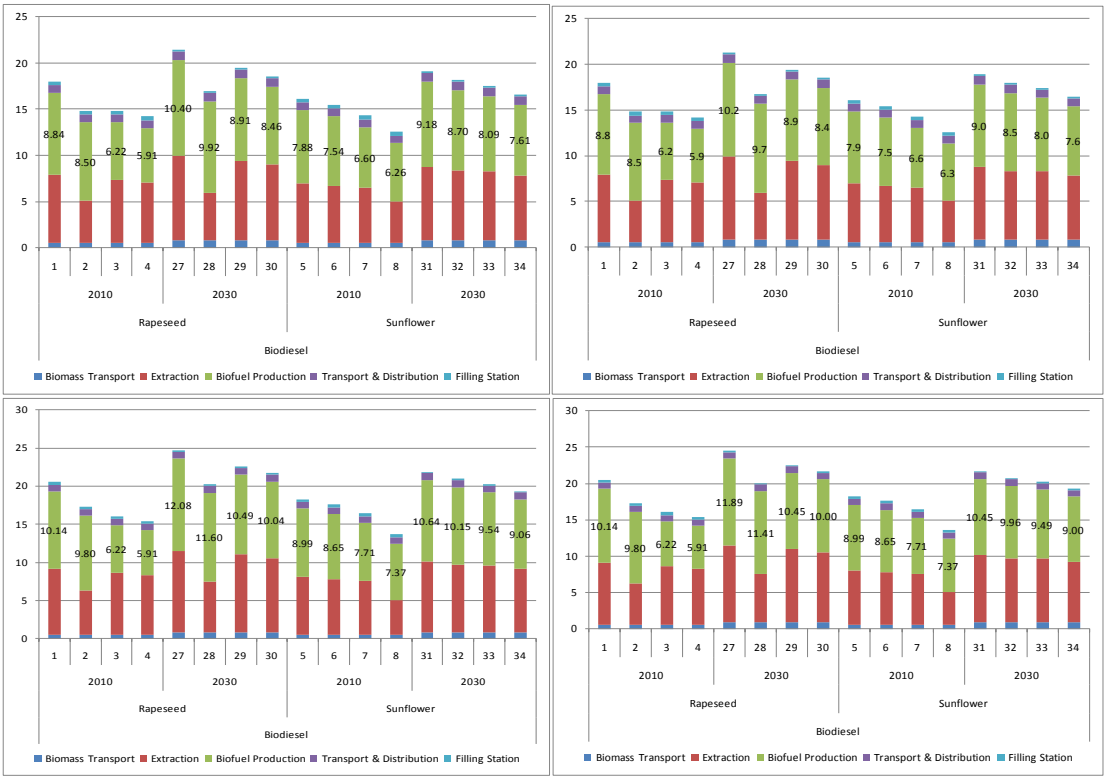


Figure 6: Results of the integrated WTT analysis (economic performance) for Biodiesel pathways for scenario I and II (up) and technology learning (right side graphs)- [c/kWh]

For biodiesel, as observed in the figures, pathways corresponding to large scale facility production, taking into account by-products credits, perform better with respect to economics (and emissions). The major part of the costs for all pathways corresponds to the extraction and production, especially the biomass feedstock prices varying from 50 to 85% of total producing costs. Oil extraction and subsequent biodiesel production are highly sensible to the variation on agricultural production costs.

Bioethanol pathways are grouped for starch (cereals) and sugar-beet crops and lignocellulosic biomass options (straw-2nd generation). The results indicate that the largest part of the costs for all options correspond to bioethanol production, of which the biggest share corresponds to the biomass costs and delivery at the bioethanol production facilities. Non-agricultural biomass feedstock (e.g. Straw) is less vulnerable to feedstock prices changes than the agricultural feedstock for 1st generation bioethanol, exhibiting higher vulnerability to volatile sugar and cereals markets. The benefits from increased learning rates remain marginal for

[1] Biodiesel from Rapeseed in *large scale* facility without by-products credits. Pathway 2 considers by-products also large scale. Pathway 3 and 4 are small scales with the same by-products considerations.

most of the producing options despite of a strong increase in experience (lower ratios) and therefore lower costs.

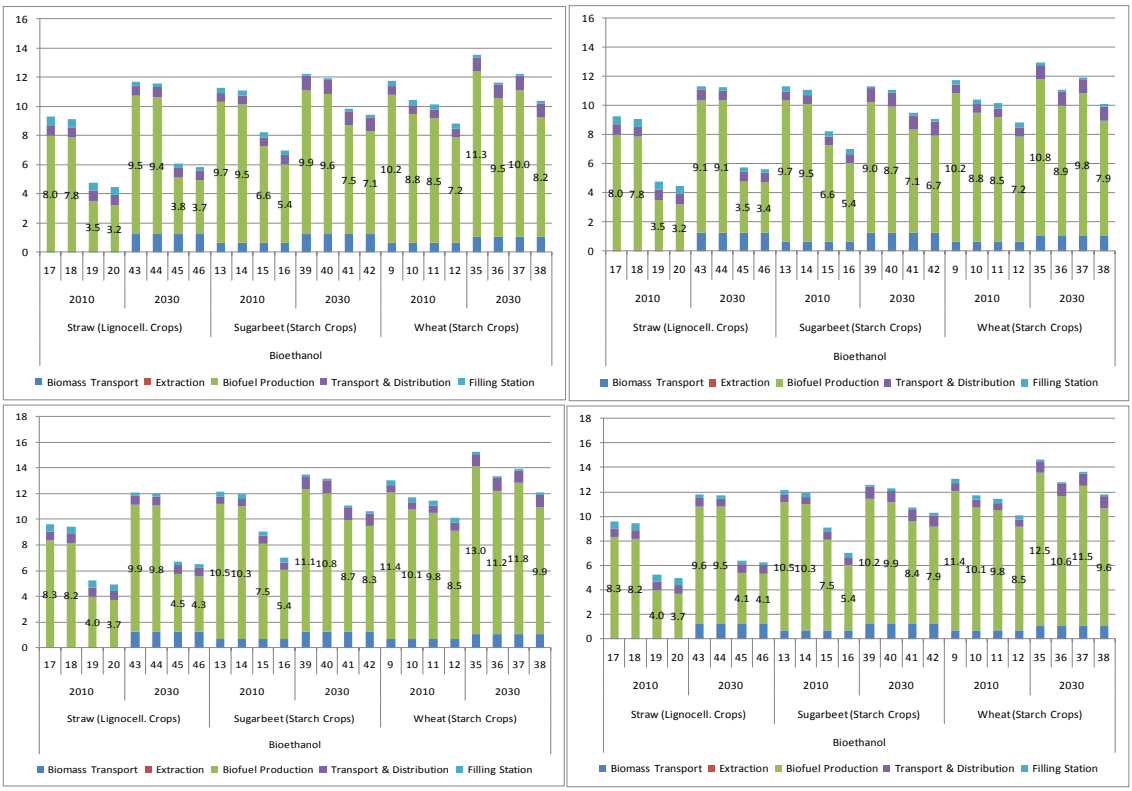


Figure 7: Results of the integrated WTT analysis (costs) for Bioethanol pathways for scenario I and II and technology learning (right side graphs)

The best cost performance corresponds to large scale plants considering by-products credits for animal feed substitution for both cereal and sugar crops. Large scale lignocellulosic bioethanol performs also better in 2010 while in 2030 it also demands logistically an organized supply of straw, however outperform compared to 1st generation options in *reference and high price* scenarios. However, such a facility does not exist currently in the market and this is just an indicative value of the cost ranges of these technologies. Furthermore, short rotation crops (wood) as feedstock for the production of bioethanol with similar plant characteristics have been used in the analysis. This technology is still in development phase and it could mean that higher capital expenditures, especially for large capacities are needed. This technology will enter the market only around 2010 and onwards, and efficiency improvements as well as capacity enlargements are expected to reduce costs in the future. Within the results, the highest emission reduction potentials are obtained for BTL facilities as the energy spent in the process is recovered using the co-generated gas to produce electricity and heat that can be reused internally in the process (self-sufficiency). Followed by the BTL facilities, the second highest reduction potentials are obtained from lignocellulosic ethanol. For biodiesel and bioethanol further emissions improvements are achieved when considering by-products credits as they substitute other materials.

5. Conclusions

The strong dependency of 1st generation alternative fuels on agricultural feedstock is observed in the results for their reference and high price scenarios developments. These technologies have still the potential to achieve costs reductions through learning, increase production, economies of scale; however, the results presented here only show a marginal benefit to increase economic performance. The high volatility of agricultural markets combined with

strong climatic changes and increase in food demand poses higher pressures to producers to develop strategies that keep supply prices down. However, the results of this analysis indicate that large scales plants might have the possibility to perform better than smaller producers, partially also reflected on the possibility to have stocks (not modeled here), however, there are high direct increases in the economic performances of these options in these kind of fuels in high price scenarios prospects. Bioethanol pathways (2nd generation (4-9.5 c/kWh) and starch/cereals 8-11 c/kWh) are close to get competitive with diesel projected prices in 2030 for both large and small scale configurations with by-products credits. Biodiesel inputs are strongly correlated with diesel prices increases and therefore results indicate that these pathways remain uncompetitive. BTL results for high price scenario considering stronger technology learning (ca. 7.8 - 12 c/kWh) are closer to be competitive to diesel projected prices in 2030 for large scale configurations with centralized biomass treatment concepts.

Furthermore, advanced AFs (2nd generation biofuels) that are in R&D and Demonstration phase (non commercial technologies) pose higher risks for investors despite of the fact that they could have faster technology learning when entering the markets especially for certain portions of second generation routes such as lignocellulosic, BTL and Hydrogen. These options are high capital intensive with still unresolved technological challenges on biomass supply possibilities; meet end-use properties like energy content, chemical stability, refueling infrastructure, storage and ex-ante feedstock price projections. The better economic performance observed in these results are partially true in case lower biomass waste streams are used or high value by-products (co-generation) add to the income flows. However, these results should be considered cautiously as the input data for the simulation is based on data that is to be proved in real operating conditions that at the moment can only be obtained by demonstration or pilot projects. In emissions terms, pathways performing better relate to the ones where by-products credits are taken into account especially co-generation plants which definitely will reflect emissions reductions, requiring on the other hand more investments for additional facilities.

References

[1] Toro F, Hasenauer U, Wietschel M, Schade W (2008): Technology trajectories for transport and its energy supply.
[2] Toro, F. Techno-Economic Assessment of Biofuels in Europe, Working Paper Fraunhofer ISI, 2004, 2005.
[3] CONCAWE, EUCAR, JRC EU Commission, Well to Tank Reports, 2006, 2007, 2008.
[4] Toro, F. A., Reitze, F., Ajanovic, A., Hass, R., et al. (2010). State of the art for alternative fuels and alternative automotive technologies. Karlsruhe, Germany.
[5] Argote, Linda; Beckman, Sara L.; Epple, Dennis, 1990. 'The Persistence and Transfer of Learning in Industrial Settings'. Management Science 36(2): 140-154
[6] Dutton, John M.; Thomas, Annie, 1984. 'Treating Progress Functions as a Managerial Opportunity'. Academy of Management Review 9(2): 235-247
[7] Resch, G., Faber, T., Haas, R., and Huber, C. (2004): Experience Curves vs Dynamic Cost-Resource Curves. In: Energy & Environment, 15, pp. 309-321.
[8] Resch, G., Held, A., Toro, F., Haas, R., et. al., (2008): Potentials and prospects for renewable energies at global scale. In: Energy Policy, 36 (11), pp. 4048-4056.
[9] Toro, F.; Held, A., Ragwitz, M.; (2009): Assessment of the Potentials for Renewable Energy Sources. In: Ball, M.; Wietschel, M. (eds.): The Hydrogen Economy. Cambridge University Press, Cambridge, pp. 135-168.
[10] E4tech (2008): Biofuels Review: Greenhouse gas saving calculations; for the Renewable Fuels Agency, June 2008.
[11] OECD/FAO (2009). OECD-FAO Agricultural Outlook 2009-2018

Impact of Plug-in Hybrid Electric Vehicles on Tehran's Electricity Distribution Grid

S. M. Hakimi[1,*], S. M. Moghaddas-Tafrshi[2]

[1] *K. N. Toosi University, Terhran, Iran*
[2] *K. N. Toosi University, Terhran, Iran*
Energy Management and Distribution Lab
** Corresponding author. Tel: +989124798639, Fax: +982188462066, E-mail: sm_hakimi@ieee.org*

Abstract: Hybrid electric vehicles (HEVs) are commercialized and plug-in hybrid electric vehicles (PHEVs) are becoming more popular. PHEVs are charged by plugging into electric outlets or on-board electricity generation. These vehicles can drive at full power in electric-only mode over a limited range. As such, PHEVs offer valuable fuel flexibility. The charging of PHEVs has an impact on the distribution grid because these vehicles consume a large amount of electrical energy and this demand of electrical power can lead to extra large and undesirable peaks in the electrical consumption. The improvements in power quality that are possible by using coordinated charging are emphasized in. It also indicates that not coordinating the charging of PHEVs decreases the efficiency of the distribution grid operation. Several automakers are preparing for the next generation of passenger transportation, Plug-in Hybrid Electric Vehicles (PHEVs). Using data from the Tehran Regional Electric Company (T.R.E.C), this study sought to understand how different charging scenarios for PHEVs could impact electricity demand in Tehran.

Keywords: *Plug-in hybrid electric vehicles; Charging scenario; Distribution grid*

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) are a new and upcoming technology in the transportation and power sector. As they are defined by the IEEE, these vehicles have a battery storage system of 4 kWh or more, a means of recharging the battery from an external source, and the ability to drive at least 10 miles in all electric mode [1]. These vehicles are able to run on fossil fuels, electricity, or a combination of both leading to a wide variety of advantages including reduced dependence on foreign oil, increased fuel economy, increased power efficiency, lowered greenhouse gas (GHG) emissions and vehicle-to-grid (V2G) technology [2–4]. These claims are backed by data suggesting that fueling a PHEV would cost the equivalent of 70 cents per gallon of gasoline when electricity costs 10 cents per kWh [4] and that an all electric driving range of 40 miles could lower oil consumption by two-thirds [4]. Currently, there is little storage available in the power grid so demand and generation must be perfectly matched and continuously managed to avoid frequency instabilities. PHEVs have an energy storage capacity which is rather small for each individual vehicle, but the number of vehicles will be large, yielding a significant energy storage capacity. At any given time, at least 90% of the vehicles are theoretically available for V2G [5,6]. These vehicles must be connected to the grid when idle. There must be enough vehicles plugged in during the day to provide grid services therefore it could be beneficial to give incentives to vehicle owners to stay plugged in. Most of the weekdays, vehicles follow a schedule which does not vary much from week to week [5]. The electrical storage of PHEVs could provide grid services via V2G concept and add a surplus value to the vehicle owner [7]. The reason for choosing Tehran for this study is the air pollution. Cut oil subsides in Iran is another reason for choosing Tehran for this study. At such low prices, domestic demand for energy in Iran has grown very rapidly. With the price reform, you will dampen domestic demand, which means more efficient energy use domestically, more energy available for profitable exports, and higher revenues for the country. From a domestic perspective, if prices are higher, the energy sector in Iran will become more profitable and hence be able to invest,

extract, and produce more. Furthermore, if the Iranian people are able to restrain their consumption, this will have a positive side effect on the global oil market. This will also push the domestic automobile industry to modernize itself. The country produces about 1.5 million cars per year, targeting the domestic market of 74 million people. Since gasoline is almost free, carmakers have little incentive to make their product energy efficient. But when gasoline price rises to the international level, Iranian car manufacturers will have to change the way they operate and increase the energy efficiency of their vehicles. Once this happens, Iranian-made cars will be more competitive on the export market.

2. Transition from conventional vehicles to Plug-in Hybrid Electric Vehicles (PHEV)

For the first time it was German inventor, Nikolaus Otto, who made it possible to use combustions engines in cars for the first time by the invention of the first four-stroke internal combustion engine in 1862. These types of engines are continuously being used in so-called conventional vehicles. The low-efficiency of ICE (Internal Combustion Engines) and high emission production are the most negative points about these types of vehicles. In the figure 1, the recent development in car industry is been shown.

Figure1. Schematic on development in car industry

As it can be seen from the figure (1), the first important breakthrough in car industry after the implementation of ICE in vehicles is the transfer from conventional vehicles to hybrid electric vehicles. These types of vehicles are first commenced in 1997 in Japan by the introduction of Toyota Prius. The main specification of this type of vehicle is the operation of the ICE on its efficient interval by means of a regenerative braking system. The latest generation of the vehicle is introduced in the market recently. They are mostly called PHEVs (Plug-in Hybrid Electric Vehicles) with additional capability to be charged from the grid.

3. Plug-in Hybrid Electric Vehicles (PHEV)

A PHEV is basically has the same structure as a Hybrid Electric Vehicles (HEV) but the grid charging capability is additional feature which consequently result in the necessity of higher battery capacity.

Grid connection capability in PHEVs will make it possible to coordinate energy resources for domestic consumption and also will lead to lower emission production from private cars in the business and residential areas.

The large percentage of the total emissions production is from the low-duty cars which are private and company cars. Reducing emission production is a big challenge for both developed and developing countries. On the other hand, the other major challenge in today's world in the high consumption of fossil fuels with increasing price and diminishing number of resources. Low-duty cars are one of the major sources of fossil fuel consumption. Therefore,

high fuel consumption and emission production are the major incentives to make changes in the low-duty car sector. Moreover, the new ways of electricity generation can be considered as an incentive for introduction of PHEVs.
Global green house gas emissions from the different sectors are show graphically in Figure 2. These gases are included Carbon Dioxide (72% in total), Methane (72% in total) and Nitrous oxide (26% in total) [8].

Table 1. Charging Times for Different PHEV-20s Vehicle Classes under Various Circuit Voltage and Amperage Levels

Vehicle Type	Pack Size (kWh)	Rated Pack Size (kWh)	Charging Circuit	Charging Size (kW)	Charger Rate (kWh/hr)	Time to Charge Empty Pack (hours)
Compact Car	5.1	4.1	120 V 15 Amp 120 V 20Amp 240 V 40 Amp	1.4 1.9 7.7	1 1.3 5.7	4 3 0.7
Mid-Sized Sedan	5.9	4.1	120 V 15 Amp 120 V 20Amp 240 V 40 Amp	1.4 1.9 7.7	1 1.3 5.7	4.7 3.5 0.9
Mid-Sized SUV	7.9	6.3	120 V 15 Amp 120 V 20Amp 240 V 40 Amp	1.4 1.9 7.7	1 1.3 5.7	6.3 4.7 1.1
Full-sized SUV	9.3	7.4	120 V 15 Amp 120 V 20Amp 240 V 40 Amp	1.4 1.9 7.7	1 1.3 5.7	7.4 5.6 1.3

As shown in the figure 2, 14 percent of the emissions are produced by transportation sector which is close to the industrial sector. This means that by removing the emissions from the transportation sector, the total emissions can be reduced approximately as much as industrial sector. The introduction of PHEVs can be even more interesting when the emissions from power station are low and the electricity is generated from clean resources.

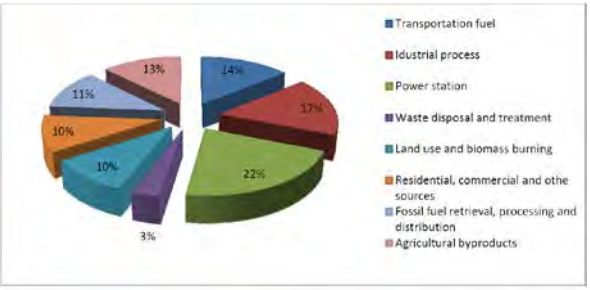


Figure2. Global Green house gasses emissions [8].

Conversion of the cars from the ones with fossil fuel consumption to the ones with electricity consumption is not just interesting from the car sector but also it is interesting from the grid point of view. The high intermittency of the electricity from renewable resources can be synchronized with the intermittency of consumption of electric cars. However, new generation is needed in order to charge the electric cars. The technical parameters of different plug-in vehicles are summarized in Table 1.

4. Plug-in Hybrid Vehicle Charging Scenarios

Electric Power Research Institute (EPRI) has performed studies regarding the energy requirements for potential PHEV vehicle designs. This information, which is summarized in Table 1, provided a basis for the charging scenarios. Figure 3 shows the power demanded for different PHEV-20 vehicle classes using a standard household electrical circuit of 120 volts and 15 amperes.

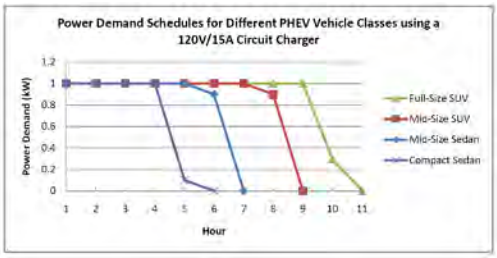


Figure 3. Power Demand Schedules for Different PHEV Vehicle Classes using a 120V/15A Circuit Charger.

The power demand schedules in Figure 3 show a consistent draw of power for the first few hours and then a partial power demand during the last hour of charging. For example, the Compact Sedan PHEV-20 requires 4.1 kWh of energy to fully recharge the battery from a 20% SOC. 1.0 kW of power is needed over the first 4 hours, and 0.1 kW during the 5th hour. This compact sedan therefore would require 4.1 hours to recharge at a rate of 1.0 kW per hour. Since most household outlets already contain 120 volt/15 amp outlets, it was assumed that most PHEVs that reach the market will charge through these circuits. Mid-sized sedan plug-in hybrids with all-electric ranges of 20 miles were used as the standard in the baseline scenarios. Variations to the electric range were used later in this paper. Using the information on charging rates and battery capacity, PHEV power demand curves were generated based around three types of charging scenarios.

The three scenarios representing how vehicle owners might charge their vehicles in the course of a day are summarized below:

Simultaneous Charging: All PHEV owners charge their vehicles at a specified time. This scenario is an adequate upper limit since recharging all the vehicles at one time maximizes the power demanded by plug-in hybrids

.

Continuous Charging: A random percent of PHEVs are connected to the grid throughout the day, requiring a continuous demand of power. A random value between 1% and 50% were established for each hour, representing the percent of PHEVs that are connected to the grid.

Normal Distribution Charging: PHEV charging follows a normal distribution around a specific hour of the day (or mean hour). This represents a scenario between the two limits.

For the simultaneous and normal distribution charging scenarios, an evening charge time of 6 pm is used for the baseline. In the simultaneous charging scenario all PHEVs plug in at 6 pm. For the normal distribution recharge, most of the PHEVs begin charging between the hours of 4 pm and 8 pm (mean hour of 6 pm and standard deviation of 2 hours). Combining the charging scenarios above with the time of day charge and charging circuit size provided the baseline scenarios for this study. Each of these is scenarios are summarized in Table 2.

Table 2. Description of Baseline Scenarios

Scenario	
Scenario 1	All mid-sized sedan PHEV-20s begin charging at 6 pm using 120V/15A charging circuits.
Scenario 2	A random percent between 1% and 50% of mid-sized sedan PHEV-20s charge throughout the day, using 120V/15A charging circuits.
Scenario 3	Mid-sized sedan PHEV-20s charge as a normal distribution about mean hour 6 pm, with a standard deviation of 2 hours, using 120V/15A charging circuits.

Different penetrations of plug-in hybrids were used with each of the charge scenarios above. The PHEVs penetrations represented 5%, 10%, 15%, and 20% of the number of registered vehicles in Tehran.

5. Baseline Charging Scenarios

Using knowledge from previous EPRI studies on lithium-ion battery technology and power demand (table 1), baseline scenarios were created and applied to electricity load demand from the Tehran Regional Electric Company (T.R.E.C). The results from the different baseline scenarios are presented with peak load day. As a reference, the average load in August 2010 is also shown. Figure 4 provides a visual representation of how different penetrations of PHEV-20s recharging at typical household electrical outlets might affect electricity load in Tehran.

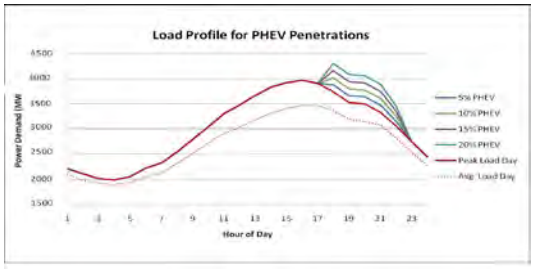


Figure 4. Load profile for PHEV-20 with varying penetrations charging under Scenario 1.

As shown by the peak load day and average August load curves, electricity load is the lowest (below 2500MW) between midnight and 8 am. Electricity generation begins to ramp up starting at 4 am up until 4 pm where it peaks. Electricity load decreases at a faster rate than its initial ramp-up and between the hours of 7 pm and 9 pm, load levels are sustained for a brief period. Peak hours roughly occur between 2 pm and 6 pm. The scenario above represents vehicle owners that all recharge at the same time in the evening (6pm) resulting in a sudden spike in demand.

Figure 5 represents a continuous charging scenario, where up to 50% of PHEV owners could begin to recharge their vehicles at any one particular time. While its probable that PHEV owners will follow a more structured recharge pattern, this scenario helps demonstrate how free access to recharging can spread the demand throughout the day, with slight fluctuations.

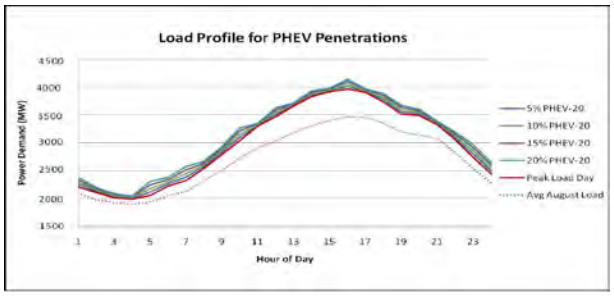


Figure 5. Load profile for PHEV-20 with varying penetrations charging under Scenario 2.

The amount of PHEV-20s that are allowed to charge at any given time is constrained to 50% in the above figure. Open access to the power grid for PHEV owners in this scenario distributes the additional power demand throughout the day, creating a completely new load profile curve.

A more realistic scenario is represented in Figure 6, where recharging occurs as a normal distribution around a specific time period. In this case, it is assumed that most PHEV-20 owners will begin recharging once home from work, around 6 pm.

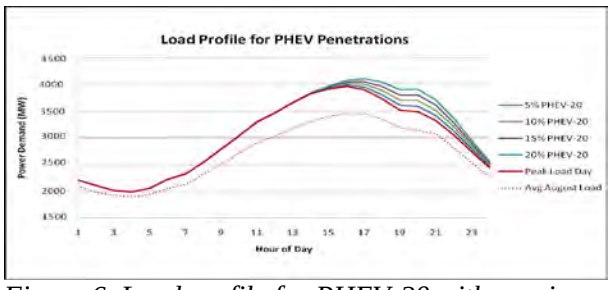


Figure 6. Load profile for PHEV-20 with varying penetrations charging under Scenario 3.

Under Scenario 3, the initial wave of PHEV owners begin charging at 3 pm, and at 6 pm, almost 20% of the owners begin charging. Since the PHEV-20s that connected to the grid between 3 and 5 pm still have not finished fully charging, this lengthens the amount of load necessary to meet demand. The maximum additional electricity demand in this scenario occurs around 8 pm and the last set of PHEV-owners charge at 10 pm, requiring additional power into the late nighttime hours.

The additional power demand at any given hour for the simultaneous scenario represents the load that is sustained for the duration of the charge, in this case, over four hours. Whereas the

simultaneous demand occurs over a short period, the continuous charging maintains a consistent load on the grid throughout the day with much smaller power required. The range for the normal distribution scenarios display the lowest power demand when the fewest PHEV-20s are charging, and the largest demand which occurs at 8 pm, when most vehicles are connected to the grid.

6. Time of Day Charging Variations

The first variation from the baseline scenario is altering the time of day that charging of plug-in hybrid vehicles begin. Shifting the charging to the morning creates the potential for additional load during peak hours. Figure 7 below shows the load profile for the peak day, applying a morning (mean hour of 9 am) charge to the load curve.

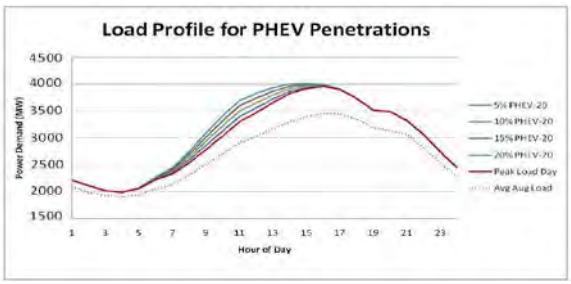


Figure 7. Load profile for PHEV-20 with aarying penetrations charging under a morning (9 am) normal distribution scenario.

As the morning charging scenario demonstrates additional that could occur when PHEV owners plug-in their vehicles after the morning commute leg, the following scenario shows how a nighttime charging scenario might impact Tehran's grid, as shown in Figure 8.

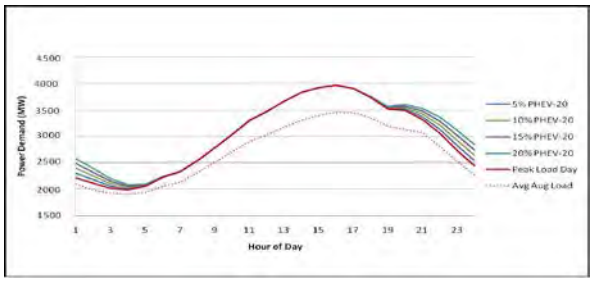


Figure 8. Load Profile for PHEV-20 with Varying Market Penetrations Charging under a Nighttime (10 pm) Normal Distribution Scenario.

Charging the PHEV-20s around a mean hour of 10 pm creates additional demand during the hours when load is diminishing, and reaches into hours when load is the lowest (3 and 4 am). Although the additional demand by PHEVs will ultimately require more electricity generation, charging during the nighttime hours, as shown above, helps to flatten the load curve. Utilizing electricity generation resources into hours when load is low and some electricity is unused, improves efficiency. Although more electricity supply is necessary to meet the demand from PHEVs in all cases, charging at night reduces the need for generating resources to be turned off and back on again.

7. Discussion

Under the simultaneous charging sharp increases can incur and although this is unlikely, it is important to understand this as a potential worst case scenario. The second recharge scenario, where less than 50% of PHEV owners are actively charging their vehicles, the overall load

profile experiences a shift to meet the elevated demand. Although vehicle owners may have the capability to recharge their vehicles multiple times per day, due to the smaller battery power capacity of PHEV-20, vehicle owners may not frequently recharge. For longer electric range PHEVs, such as a PHEV-60, or larger vehicle designs, such as Sport Utility Vehicles (SUVs) which require more energy, the battery may require multiple recharges throughout the day, if the goal is to fully utilize electric drive capability. The final recharge scenario, where recharging follows a normal distribution around 6pm, demonstrates a more realistic behavior pattern. While no sharp increases in demand are expected, it is anticipated that a gradual ramp up in load demand occur during the late afternoon hours and that these resources would be utilized into the evening hours.

8. Conclusion

The results of the study have provided insight into the how Tehran's electricity grid may be impacted from the introduction of plug-in hybrid vehicles. Hours of the day when recharging is expected to occur in large numbers, such as when commuters arrive home from work, can have significant impacts on demand. In the absence of dramatic infrastructure changes with respect to charging stations for PHEVs, most owners will recharge using standard 120V/15A electrical outlets. The charging of PHEV-20 under a 120V/15A circuit would not inconvenience most vehicle owners. The time of day for recharging plug-in hybrid vehicles is an important factor to be considered when planning for this new technology. Late evening hour recharges create additional demand when electricity generation begins to ramp down, only requiring existing generating units to be utilized for a longer duration. If the addition of recharge stations in parking lots where incorporated into the scenario, it would be possible for a portion of vehicle owners to recharge when generation is beginning to ramp up, as shown in the morning charging scenarios.

References

[1] IEEE USA. Plug-in electric hybrid vehicles. Position statement adopted by IEEEUSA board of directors; 2007.

[2] Duvall M. Comparing the benefits and impacts of hybrid electric vehicle options for compact sedan and sport utility vehicles. Technical Report of EPRI 2002.

[3] Li X, Lopes LAC, Williamson SS. On the suitability of plug-in hybrid electric vehicle (phev) charging infrastructures based on wind and solar energy. IEEE Power & Energy Society General Meeting 2009; 1–8.

[4] Dickerman L, Harrison J. A new car, a new grid. IEEE Power and Energy Magazine 2010; 8(2):55–61.

[5] S.D. Jenkins, J. Rossmaier, M. Ferdowsi, Utilization and effect of plug-in hybrid electric vehicles in the united states power grid, in: IEEE Vehicle and Propulsion Conference (VPPC), 2008.

[6] S.G. Wirasingha, N. Schofield, A. Emadi, Plug-in hybrid electric vehicle developments in the US: trends, barriers, and economic feasibility, in: IEEE Vehicle Power and Propulsion Conference (VPPC), 2008.

[7] P. Denholm, S. Letendre, Grid services from plug-in hybrid electric vehicles: a key to economic viability? National Renewable Energy Laboratory, Tech. Rep.

[8] Rosmarino, Tanyalynnette. A Self-Funding Enterprise Solution to Reduce Power Consumption and Carbon Emissions.

Analysis of the CO_2 and energy demand reduction potentials of passenger vehicles based on the simulation of technical improvements until 2030

Felipe Toro[1*], Felix Reitze[1], Sulabh Jain[2], Eberhard Jochem[1,3]

[1] *Institute for Resource Efficiency and Energy Strategies IREES, Karlsruhe, Germany*
[2] *TU Bergakademie Freiberg, Freiberg, Germany*
[3] *Centre for Energy Policy, ETH Zurich, Switzerland*
**Felipe Toro. Tel: +49-721-915263621, Fax:+49-721-915263611, email: f.toro@irees.de*

Abstract: In Europe, passenger cars use over 65% of total transport fuel energy and produce around 12% of total EU carbon emissions. Under such circumstances advanced technologies and modifications in multiple powertrain technologies in passenger cars hold an important key to reduce emissions and energy demand into future. This study compiles a set of efficiency improvement technologies and makes use of a 'Bottom-up simulation' to assess the effects of introduction these technologies on total energy demand and CO_2 emission from passenger cars up to 2030 in the EU-27. The integration of improvement technologies in vehicle will serve the purpose of increasing fuel efficiency, enhancing performance and provide further technical and environmental benefits, but it will also result in incremental costs over the vehicle baseline prices. This research also assesses changes in specific driving costs, cost of CO_2 avoidance and the payback period of incremental costs on the vehicle's economic performance. The technical improvement potentials' options considered in this study show that a 5% to 22% increase in fuel economy of car is possible. And based on assumed diffusion of technologies across total gasoline and diesel vehicles, this study infers a potential of 19% to 34% savings in energy demand and CO_2 emission by 2030.

Keywords: *Low carbon vehicles, Vehicles innovation, Energy efficiency, Bottom-up modelling, Technology market diffusion*

1. Introduction

Across Europe cars have given the public greatest mobility that is adjustable to different usages, driving locations and preferences, and this trend will continue to grow into future. Over the last few years, increasing environmental concerns, rising oil prices and continuous urge for technological developments have stimulated industries and nations across the world to move towards better efficiency and sustainable practices in the transport sector. To tackle the problems associated with constantly increasing transport fossil fuel demand and greenhouse gas (GHG) emission, it has become very important to consider the alternative fuels and alternative cars for meeting environmental benefits.

In the last few years, the European car manufacturers have invested significant amount of money in the technology R&D, and have introduced more than 50 advanced technologies into the cars for the purpose of efficiency gain and emission reduction. In addition to the varied upcoming vehicle technologies like battery electric vehicles and hydrogen fuel cell vehicles, nowadays a large number of vehicle and powertrain improvement technologies are aimed at increasing the fuel economy and efficiency of the existing conventional vehicles through technical improvements. The core analysis of this paper is based on such 'technical improvement potentials'. This paper is an extension of an ongoing research under the project ALTERMOTIVE, contracted under Intelligent Energy Europe.

Currently, a huge diversity of fuels and advanced powertrain technologies are available in Europe. Table 1 states various alternative automotive mobility technologies (AAMTs) mapped under different developmental stages along the technology curve (Research, Demonstration and/or Commercial state). In Table 1 it can be seen that in addition to the conventional diesel and gasoline cars, few other AAMTs like Natural Gas Vehicles and Flexi

Fuel Cars already exist in the European market on commercial level. These technologies also show continuous process of developments for achieving higher vehicle efficiency and better customer satisfaction. The technologies included under Demonstration phase are not at commercial scale yet, but depending on the speed of progress and overcoming market and cost barriers these may come to commercial phase in next few years. The technologies exhibiting the R&D phase will continue to progress to overcome technical challenges and incompatibilities, and will come to commercial phase no sooner than 2020-2025.

Table 1: Alternative Automotive Mobility Technologies - State of the Art in Europe (2010)

	Commercial	Demonstration	R&D
Technologies	**NG (LNG/CNG)** **Flex-Fuel Vehicle** *(conventional fuel + BD/BE)* **Bi-fuels** *(NG + Gasoline/Diesel)* **Gasoline-Electric Hybrid** **Electric Vehicles:** *Micro-Mild Hybrid* *BEV (only light vehicles, no convertor, DC Motor, Range<100 km*	**Solo/High blend BE** **Diesel-Electric Hybrid** **Electric Vehicles:** *Enhanced HEV-PHEV* *BEV (with convertor, AC Motor, Range > 100 km)* *Full Hybrid* **FC hybrids** *(conventional fuel + hydrogen)*	**Solo/High blend BD** **Biogas** **Electric vehicles:** *FCV- PHEV (Plug-In functionality for FCV/HEV)* *BEV (with convertor, AC Motor)* **FCV**

Source: (Toro, et al., 2010)

Abbreviations = NG: Natural Gas, LNG: Liquid NG, CNG: Compressed NG, BD: Biodiesel, BE: Bioethanol, EV: Electric Vehicle, HEV: Hybrid EV, BEV: Battery EV, PHEV: Plug-in Hybrid EV, DC: Direct Current, AC: Alternative Current, FC: Fuel Cell, FCV: FC Vehicle

2. Methodology

The method implemented for this study starts with the review of various technical improvement potentials in the European passenger cars along with their potentials in enhancing the vehicle efficiency. In next step, this study selects two sets of innovative improvement technologies called as 'Technology Option 1 & 2' and assesses the impacts of their integration on vehicle's energy demand, CO_2 emission, and economic performance. The main assessments applied in this study with the bottom-up simulation and economic estimations are:

1. Assessing the improvements in the vehicular energy consumption and consecutive CO_2 emission as a result of integration of Technology Options – Techno-Environmental assessment.
2. Assessing the changes in economic performance of the car as a result of incremental costs and technical improvements – Economic assessment.
3. Assessing the potentials of technologies in overall energy demand and emission reduction at assumed diffusion rates across EU-27 car fleet – Techno-Environmental assessment.

2.1. Techno-Environmental assessment:

The techno-environmental assessment carried through the bottom-up simulation is done to assess the energy demand and CO_2 emission by the total European passenger cars (including all types' such as gasoline, diesel, hybrid, bioethanol etc.) for a fixed annual driving distance. For setting up an energy demand baseline, energy demand projections and car fleet size

forecasts in EU-27 until 2030 were derived from Fiorello, et al., (2009). Then the bottom-up simulation tool was built up by using different vehicular data and other input values (like fuel economy, average annual traveling etc.) to assess the overall energy demand and CO_2 emission up to 2030. The general formula for the assessment is:

$$ED_t = \sum\left(F_{i,t} \times D_{i,t} \times FE_{i,t}\right) \qquad \text{[PJ]} \qquad \text{Eq. 1}$$

Where, ED_t is the total energy demand (including different fuels *Fu*) in the year *t*, *i* is the model year, *F* is the number of vehicles of a model year *i* running in year *t* on fuel *Fu*. *D* is the annual distance travelled by a car of model year *i* in year *t* using fuel *Fu*. *FE* is the average fuel economy (MJ/100km) of the car for a model year *i*, using fuel *Fu* running in year *t*.

Changes in fuel economy: It was considered that when the technical improvements occur into the car by implementation of *'Technology Options'*, the fuel economy increases by a certain %. The equation used to assess changes in the fuel economy is:

$$FE_e = FE_b \times \ (1 - \%E_{TO}) \qquad \text{[MJ/100km]} \qquad \text{Eq. 2}$$

Where, FE_e is the enhanced fuel economy, FE_b is the baseline fuel economy of the vehicle and $\%E_{TO}$ is the percent (%) by which the *'Technology Option'* enhances the vehicle efficiency.

2.2. Economic assessment:

The fuel efficiency of the vehicle can be enhanced by implementation of advanced innovative technologies, but the introduction of new technologies in vehicle will cause extra upfront investments and additional costs to the manufacturers and these costs will add extra price over the vehicle price (McKinsey, 2009). Thus, it is technically feasible to reduce the fuel consumption of new vehicles, but additional costs will be incurred. In this study, following assessments were done.

Incremental Cost of technology options: The concept of Retail Price Equivalent Multiplier (RPE factor) that represents the average additional price consumers would need to pay for an advanced technology was used to assess the incremental costs of technologies.

$$IC_{TO} = C_M \times RPE\ factor \qquad \text{Eq. 3}$$

Where IC_{TO} is the incremental cost of Technology Option, C_M is the manufacturer cost of technologies (derived from AEA, 2009) and *RPE factor* is the retail price equivalent multiplier (derived from Vyas, et al., 2000; NRC, 2010).

Specific Driving Costs: the cost of driving per kilometer of vehicle. This cost in the analysis was interpreted as an aggregate construct of vehicle investment costs linked to 8% annual O&M costs, fixed annual driving distance and the vehicle lifetime of 10 years.

$$\boldsymbol{SC_d = \frac{I_a + O\&M}{D_{annual}}} \qquad \text{[€/km]} \qquad \text{Eq. 4}$$

Where, SC_d is the specific driving cost, I_a is the annual investment cost, *O&M* is the operation and maintenance cost and D_{annual} is the annual distance travelled by the car.

Average payback Period: It is the time period in which the incremental costs can be compensated by the monetary savings that occur as a result of decreased fuel demand by technical improvement.

$$PB_{avg} = \frac{C_i}{YS_{€/a}} \qquad \text{[Years]} \qquad \text{Eq. 5}$$

Where, PB_{avg} is the average payback period, C_i is the incremental cost and $YS_{€/a}$ is the annual monetary saving (€/a) per year through reduced fuel expenditure.

Cost of CO_2 avoidance or CO_2 abatement costs: It is assumed that for a technically improved vehicle the driver has to bear extra investment costs over the vehicle price. So, how much does it cost (in €) to the driver for saving each tonne of CO_2 is called the cost of CO_2 avoidance. It is calculated by the following formula.

$$CO_2\ abatement\ cost = \frac{C_i}{Tonne\ CO_{2\ saved}} \qquad \text{[€/tonnne]} \qquad \text{Eq. 6}$$

Where, C_i is the incremental cost and Tonne CO_{2saved} is the CO_2 saved within vehicle life time.

2.3. Sources, Data and Assumptions:

2.3.1. iTREN Reference Scenario (Deliverable-4, 2009): Fiorello, et al., (2009)

This report was chosen for fleet characteristics and energy demand projections as it delivers the quantified data in Europe until 2030 and more importantly the assessment carried in the study does not consider any technical improvements of the cars after 2008. Table 2 states the data and values extracted from Fiorello, et al., (2009).

Table 2 : Baseline values and assumptions (EU-27 passenger car fleet)

	Unit	2005	2010	2020	2030
Total no.of cars-EU-27	1,000 vehicles	211,062	228,120	265,628	294,220
Total Energy Demand	PJ	8,435	9,251	9,630	10,301
CO_2 emissions*	Million tonnes/year	624	684	712	761
Emissions	MillionTonnes/year	793	760	833	840
Gasoline Price	€/litre	1.07	1.40	1.27	1.34
Diesel Price	€/litre	0.92	1.25	1.16	1.24

*Source: (Fiorello, et al., 2009), *Calculated by Authors*

2.3.2. Concawe (WTW, Version-2b, 2006 and TTW, Version-3, 2008)

Average characteristics and data for the European passenger cars like vehicle price, engine power, fuel economy, fuel specific emission factor of the fuel etc. were derived from the Concawe reports mentioned above. Table 3 states the data derived for gasoline and diesel cars.

Table 3: Data and values derived from Concawe reports

	Unit	Gasoline	Diesel
Vehicle Price	€	19,000	20,000
Capacity Fuel/Engine Power	kW	77	74
Av. Travelling distance*	Km/yr	18,000	20,000
GHG emission	gm CO_2 eq.per km	165	140
Specific driving costs*	€/100 km	24.18	22.90

Source: (Concawe, 2008)*; *Authors' assumption/calculations*

2.4. Efficiency Improvement Technologies

There are many efficiency improvement technologies that can be introduced in today's vehicles without changing the vehicle's basic type, general size, or performance. Virtually all of the technologies are capable of increasing vehicle efficiency and reducing fuel demand, but they all are not equally ready for the commercial production. The technologies grouped as Technology option 1 and 2 in Table 4 were chosen based on their readiness as they are applicable into the conventional diesel and gasoline passenger cars within 2010-2012 timeframe.

Table 4: Technology Options considered for the study

	Technology Option 1	*Technology Option 2*
Technology Combination	1. Reduced engine friction losses 2. Improved aerodynamics 3. Low rolling resistance tyres	1. Improved aerodynamics 2. Vehicle Weight reduction 3. Optimized transmission 4. Mild downsizing with Turbo Charging 5. Start-stop-system 6. Use of advanced devices (tyre pressure monitoring system, gear shift indicator etc.)
Expected efficiency increase	Around 5%	Around 22%
Source - eff. Increase	(EPA, 2008)	(McKinsey, 2009)
Tech. cost assumption*	10% over car baseline price	30% over car baseline price
Status in Europe	Integrated into new cars by most manufacturers	High consideration for application

**Source: (TNO, 2006), (AEA, 2009)*

2.5. Technology Diffusion Assumption

The term technology diffusion in this study refers to the widespread integration of Technology Options into the new European gasoline and diesel cars up to 2030. For the simulation, the diffusion was considered only within gasoline and diesel cars because both the Technology Options are compatible into these cars without rendering any change to the size or performance of the car. Moreover, gasoline and diesel cars represent the biggest share in the total EU-27 car fleet and this trend of majority will continue to increase at least until 2030.

To build the stock of new cars in EU-27 until 2030, a review of historical vehicle registration data and socio-economic developments was done. Then the review was complemented with the expected GDP growth to establish the expected trend of new car registrations in EU-27.

The two scenarios considered for this study are:

Scenario 1: Technical Potential - Assessment of the maximum energy demand and CO_2 emission reduction potential offered by the technologies under the assumption that Technology Option 2 diffuses extensively across the fleet.

Scenario 2: Autonomous Potential - Assessment of the reduction potential form the technologies under the assumption that the Technology Option 2 diffuses to a limited extent within the new fleet, however followed by autonomous technological progress the Technology Option 1 diffuses widely across the fleet.

Table 5: Technology Diffusion Assumption

		2010	2015	2020	2025	2030
Scenario 1 (Tech.Pot)	Diffusion of Tech. Op 2 into new cars	10%	30%	50%	75%	100%
	Diffusion of Tech. Op 2 into old cars	10%	20%	25%	30%	25%
Scenario 2 (Auto.Pot)	Diffusion of Tech. Op 2 into new cars	10%	15%	20%	30%	35%
	Diffusion of Tech. Op 2 into old cars	10%	15%	18%	20%	20%

3. Results

The results presented in Table 6 are derived by considering the integration of Technology Options into the vehicle. The assessment methods for the techno-environmental and economic assessment take into account all the salient aspects like baseline vehicle price, additional investment costs Technology Options, engine size and fuel capacity, yearly driving distance, diesel and gasoline fuel price projections until 2030 from (Fiorello, et al., 2009).

Table 6: Results of techno-environmental and economic assessments at the vehicular level

Assessed value	Unit	Baseline value (G)	Gasoline Car		Baseline value (D)	Diesel Car	
			Tech. Op.1	Tech. Op.2		Tech. Op.1	Tech. Op.2
Average cost of *'Technology Option'*	€	-	350	2,800	-	350	2,450
Sp. Driving Costs	€/100 km	24.18	24.62	27.74	22.90	23.30	25.71
Fuel economy	MJ/100km	220	209	171.6	190	180.5	148.2
Specific CO_2 emission	gCO_2/km	165	156.8	128.7	140	133	109.2
Fuel expenses*	€/100km	9.49	9.02	7.40	6.63	6.29	5.17
Fuel economy	km/litre	14.7	15.5	18.9	18.9	19.9	24.2
Fuel economy	l/100km	6.78	6.44	5.29	5.30	5.04	4.13
Yearly energy demand	MJ/yr	39,600	37,620	30,888	38,000	36,100	29,640
Yearly CO_2 emissions	Tonnes CO_2/yr	2.94	2.80	2.30	2.79	2.65	2.18
Cost of CO_2 avoidance	€/Tonne	-	238	432	-	250	398
Average payback period*	Years	-	4.1	7.4	-	5.3	8.4

*Source: Assessed by authors, * considering 2010 fuel price from (Fiorello, et al., 2009)*

The energy demand and emission potential results presented in Table 7 show as what could be achieved when technologies are implemented into the assumed percentage of the EU-27 new gasoline and diesel cars. The scenarios developed within this study show that 19% to 34% reduction in total energy demand and subsequent CO_2 emission can be achieved by 2030.

Table 7: Results of total energy demand and emission saving potential

Results	2010	2015	2020	2025	2030
Baseline – Energy Demand (PJ)	9,253	9,439	9,630	9,959	10,300
Technical Potential (S1)	9,121	8,197	7,935	7,550	6,797
Autonomous Potential (S2)	9,186	8,600	8,514	8,344	8,328
Scenario 1/Baseline	-1.43%	-13.16%	-17.59%	-24.19%	-34.01%
Scenario 2/Baseline	-0.72%	-8.89%	-11.59%	-16.21%	-19.14%
Baseline - CO_2 emission (Mil.tonne)	684	698	712	736	761
Technical Potential (S1)	674	606	587	558	502
Autonomous Potential (S2)	679	636	629	617	615
Scenario 1/Baseline	-1.41%	-13.11%	-17.59%	-24.15%	-34.03%
Scenario 2/Baseline	-0.70%	-8.84%	-11.57%	-16.16%	-19.14%

Source: Own calculations

It is important to note that diffusion assumptions explained here are based on authors' views supported by technology readiness and expected technical developments. In reality there may be several interactions and measures (like EU policies, market behavior, cost of technologies, consumers' preference etc.) that will affect the relative effectiveness of technologies and their deployment within industry (Skinner, Essen, Smokers, & Hill, 2010). To summarize the results, Figure 1 shows the overall potentials in energy demand and CO_2 emission savings assessed within this study. The figure is converted in % savings for the ease of understanding and combining the energy demand and emission changes until 2030.

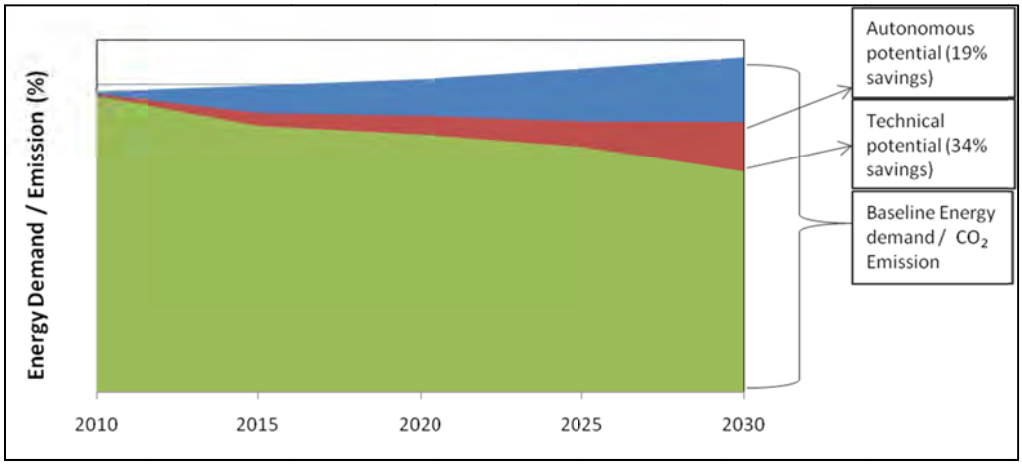


Figure 1: Total energy and CO_2 emission saving potentials
Source: Own calculations and elaboration

4. Discussion and Conclusions

The results and analysis detailed in this paper show the potentials of energy demand and CO_2 emission reduction; however, there are certain limitations in the analysis. The technologies considered in the study are based on the theoretical values and potentials for vehicle efficiency increase, but the results may vary significantly during vehicle segment applications (e.g. small, medium or large cars) and under different on-road driving conditions. Secondly, the technologies included in this study are not the only options that European car manufacturers are considering. There are many other technologies and measures that have varied degree of technology readiness and implementation within cars for the purpose of efficiency increase.

An important aspect regarding the aforementioned results is the compliance of the emission values with the EU regulations on average gCO_2/km emission. The European Commission has established the emission limiting targets by averaging emissions (g/km) of all car models weighted by the sales volumes of the manufacturers. Therefore, when the baseline emission values are compared to the EC targets then this does not imply that all the cars drive at the same mileage and emit same amount of CO_2. All car models across the Europe possess varying mileage range, therefore different vehicle models, car segments and the fuel used in them contribute differently to the average on-road CO_2 emission.

Technical improvement technologies can result in substantial improvements in new car fuel economy and subsequent GHG emission. While virtually all of the technologies are capable of enhancing vehicle efficiency, they are not equally ready for production and integration into the vehicle. Technologies included in Technology Option 1 have been widely introduced into the market until now. And, the technologies included in Technology Option 2 posses high

degree of technology readiness and high consideration by the manufacturers for integration within the current production lines.

Results stated in this study (in Table 6) have shown the increasing pattern of fuel economy in gasoline and diesel cars. Technology Options 1 & 2 have the potential to enhance vehicle efficiency by 5% and 22% respectively, which can save between 0.14 and 0.64 tonneCO_2/year per car for a fixed driving cycle. Results of economic assessment show the decreasing pattern of fuel expenditure in terms of €/100km or €/Year. The assessment shows that both the Technology Options may increase vehicle cost by 10% and 30%, but as a result of increased fuel economy and reduced fuel expenditure, the additional investment can be reimbursed within the certain time period considered as the 'Payback period'. The Technology Options are projected to result in a net cost benefit to the owner over a 10 year vehicle lifetime because the cumulative fuel expenditure savings offset the higher incremental costs. The results of technology diffusion based on bottom-up simulation show that there is a potential of between 19% and 34% reduction in the energy demand and CO_2 emission in the EU-27 up to 2030.

References

[1] Toro, F. A., Jain, S., Reitze, F., Ajanovic, A., Hass, R., Furlan, S., et al. (2010). State of the art for alternative fuels and alternative automotive technologies. Karlsruhe, Germany: Project ALTERMOTIVE: Deriving effective least cost policy strategies for alternative automotive concepts and alternative fuels.

[2] Fiorello, D., De Stasio, C., Koehler, J., Kraft, M., Newton, S., Purwanto, J., et al. (2009). *The iTREN-2030 reference scenario until 2030: Deliverable 4 of iTREN-2030.* Milan, Italy: Project co-funded by European Commission 6th RTD Programme.

[3] McKinsey. (2009). Der Trend zu energie - effizienten Pkw, Implikationen für die deutsche Automobilindustrie. McKinsey&Company.

[4] Concawe. (2008). *Weel to Wheel Analysis of Future Automotive Fuels and Powertrains in the European Context.*

[5] EPA. (2008). *EPA Staff Technical Report: Cost and Effectiveness Estimates of Technologies Used to Reduce Light-duty Vehicle Carbon Dioxide Emissions.* United States Environmental Protection Agency. US-EPA.

[6] AEA. (2009). *Assessment with respect to long term CO2 emission targets for passenger cars and vans.* AEA - Deliverable D2: Final Report.

[7] TNO. (2006). *Review and analysis of the reduction potential and costs of technological and other measures to reduce CO2-emissions from passenger cars.* Delft: TNO Science and Industry.

[8] Skinner, I., Essen, H. v., Smokers, R., & Hill, N. (2010). *Towards the decarbonisation of the EU's transport sector by 2050.* London, UK: AEA.

[9] TNO. (2006). *Review and analysis of the reduction potential and costs of technological and other measures to reduce CO2-emissions from passenger cars.* Delft: TNO Science and Industry.

[10] Skinner, I., Essen, H. v., Smokers, R., & Hill, N. (2010). *Towards the decarbonisation of the EU's transport sector by 2050.* London, UK: AEA.

Experimental performance of an R134a automobile heat pump system coupled to the passenger compartment

M. Direk[1], M. Hosoz[1,*], K.S. Yigit[2], M. Canakci[1], A. Turkcan[1], E. Alptekin[1], A. Sanli[1], A.F. Ozguc[3]

[1] *Department of Mechanical Education, Kocaeli University, 41380 Kocaeli, Turkey*
[2] *Department of Mechanical Engineering, Kocaeli University, 41040 Kocaeli, Turkey*
[3] *Department of Mechanical Engineering, Istanbul Technical University, Istanbul, 34437, Turkey*
** Corresponding author. Tel: +90 2623032279, Fax: +90 2623032203, E-mail: mhosoz@kocaeli.edu.tr*

Abstract: This study presents experimental performance of an R134a automotive heat pump (AHP) system driven by a diesel engine and capable of utilizing the heat absorbed from the ambient air, engine coolant and exhaust gas. The experimental setup was developed from the components of the air conditioning system of a compact-size car, and tested by changing the engine speed, engine load and air temperatures entering the condenser and evaporator. The steady-state and transient performance characteristics of the AHP system for each heat source were evaluated by applying energy analysis to the system based on experimental data. Then, the performance parameters of the AHP system for three different heat sources were compared with each other and with those of the baseline heating system. The results show that the AHP system using engine coolant provides higher heating capacities and air temperatures at the register outlet in the first five minutes of the tests. However, the baseline heating system usually performs better than the AHP system when the steady-state is achieved. The AHP system caused an increase in the engine brake specific fuel consumption within the range of 4–54% depending on the engine load.

Keywords: *Automotive heat pump, R134a, Refrigeration, Air conditioning, Automobile*

1. Introduction

Passenger vehicles equipped with a water-cooled internal combustion engine usually utilize the engine waste heat in order to perform comfort heating of the passenger compartment under cold weather conditions. However, this coolant-based heating system cannot provide an appropriate thermal comfort in the passenger compartment until the coolant temperature rises to a certain value. This problem is more critical for the vehicles employing high-efficiency diesel engines due to the lack of sufficient waste heat within an acceptable duration of operation after the engine is started up. With the intention of obtaining thermal comfort rapidly, some vehicles utilize heaters using fuel or electricity. However, these systems have disadvantages such as high initial and operating cost, low efficiency and leading to air pollution as well as global warming. On the other hand, the problem of insufficient heating can be solved by adding some low cost components to the present air conditioning system of the vehicle to operate it as a heat pump. The automotive heat pump (AHP) system can heat the passenger compartment individually, or it can support the present heating system of the vehicle. In the literature, there are several investigations on the performance of AHP systems. Among these studies, Domitrovic et al. [1] simulated the steady-state cooling and heating operations of an automotive air conditioning (AAC) and heat pump system using R12 and R134a, and determined the change of the cooling and heating capacities, coefficient of performance (*COP*) and power consumption with ambient temperature at a fixed compressor speed. Hosoz and Direk [2] evaluated the performance of an air-to-air R134a AHP system, and compared its performance with the performance of the air conditioning system. Rongstam and Mingrino [3] evaluated the performance of an R134a AHP system using engine coolant as a heat source, and compared it with the performance of a coolant-based heating system at an ambient temperature of –10ºC. Scherer et al. [4] reported an on-vehicle performance comparison of R152a and R134a AHP systems using engine coolant as a heat source.

Antonijevic and Heckt [5] developed and evaluated the performance an R134a AHP system, which was employed as a supplementary heating system. They carried out the tests at very low ambient temperatures and compared the performance of the AHP system with that of other supplemental heating systems.

In this study, an experimental AHP system capable of providing a conditioned air stream by utilizing the heat absorbed from the ambient air, engine coolant or exhaust gas was developed. In the experimental system, after passing through the indoor unit, the conditioned air stream was sent to the vehicle passenger compartment through a flexible air duct. In the experiments, the engine speed, engine load and air temperatures entering the condenser (indoor unit) and evaporator (outdoor unit) were controlled and concisely adjusted. The investigated performance parameters were the air temperature at the compartment front register outlet, mean air temperature in the passenger compartment, heating capacity, coefficient of performance and the increase in the brake specific fuel consumption (*BSFC*) of the engine caused by the operation of the AHP system.

2. Methodology

The experimental AHP system was usually made from the original components of an AAC system of a compact size car. As schematically shown in Fig. 1, it employs a seven-cylinder fixed-capacity swash-plate compressor, a parallel-flow micro-channel outdoor coil, a laminated type indoor coil, two thermostatic expansion valves, a reversing valve to operate the system in reverse direction in heat pump operations, a brazed plate heat exchanger between the engine coolant and the refrigerant to serve as an evaporator and another plate heat exchanger to extract heat from the exhaust gas.

All lines in the refrigeration circuit of the system were made from copper tubing, and insulated by elastomeric material. The indoor and outdoor coils were inserted into separate air ducts of 1.0 m length. In order to provide the required air streams in the air ducts, a centrifugal fan and an axial fan were placed at the entrances of the indoor and outdoor air ducts, respectively. These ducts also contain electric heaters located upstream of the indoor and outdoor coils. The indoor and outdoor coil electric heaters can be controlled between 0–2 kW and 0–6 kW, respectively, to provide the required air temperatures at the inlets of the related coils. The refrigeration circuit was charged with 1600g of R134a. In order to gather data for the performance evaluation of the experimental AHP system, some mechanical measurements were conducted on it. The employed instruments and their locations are depicted in Fig. 1, and the characteristics of the instrumentation are reported in Table 1.

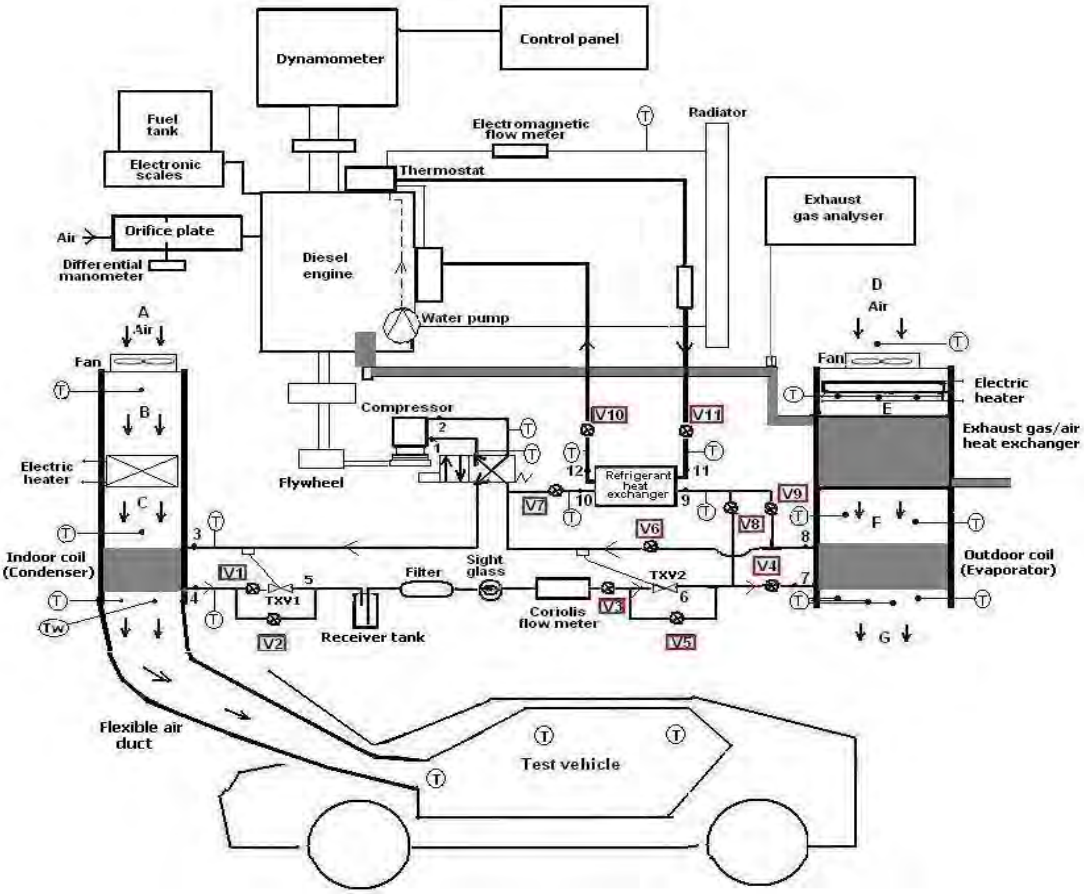


Fig. 1. Schematic illustration of the experimental AHP system and test vehicle (The arrows show the flow paths in the heat pump operations using ambient air and exhaust gas as a heat source).

Table 1. Characteristics of the instrumentation.

Measured variable	Instrument	Range	Uncertainty
Temperature	Type K thermocouple	–50–500 ºC	± % 0.3
Pressure	Pressure transmitter	0–25 bar	± % 0.2
Air speed	Anemometer	0.1–15 m s^{-1}	± % 3
Refrigerant mass flow rate	Coriolis flow meter	0–350 kg h^{-1}	± % 0.1
Compressor speed	Digital tachometer	10–100000 rpm	± % 2
Torque	Hydraulic dynamometer	5–750 Nm	± % 2

The refrigerant mass flow rate was measured by a Coriolis mass flow meter. The temperatures of the refrigerant and air at the inlet and outlet of each component were measured by K-type thermocouples. The refrigerant pressures at the inlet and outlet of the compressor were measured by both Bourdon gauges and pressure transmitters.

The AHP system was driven by a Fiat Doblo JTD diesel engine with a cylinder volume of 1900 cc and a maximum power of 77 kW at 4000 rpm. The engine torque and speed were measured by means of a hydraulic dynamometer with a maximum measuring power of 100 kW, a maximum torque of 750 Nm and a maximum speed of 6000 rpm. The fuel consumption was measured using an electronic scale and a chronometer. Most of the measurement data were acquired through a data acquisition system and recorded on a computer.

The conditioned air stream discharged from the condenser duct was supplied to the passenger compartment of the test automobile Renault Safrane. The connection between the evaporator

duct and the compartment was performed using an insulated flexible air duct. In order to measure the compartment temperatures, a thermocouple was located at the outlet of the front register, another one was suspended in the air close to the front left seat at the driver neck level, and the last one was suspended in the air close to the rear right seat at the passenger neck level.

Fig. 1 also illustrates the refrigerant flow paths in the experimental heat pump system for the cases of using ambient air or exhaust gas as a heat source. In order to perform the heat pump operation, the reversing valve is energized. Then, the reversing valve directs the high temperature superheated vapour refrigerant discharged from the compressor to the indoor coil. Afterwards, the refrigerant condensed in the indoor coil enters the outdoor unit (evaporator) through the thermostatic expansion valve (TXV2). The refrigerant evaporates by absorbing heat from the ambient air stream, which can be preheated by the exhaust gas/air heat exchanger in the heat pump operations using the exhaust gas as a heat source. Finally, the evaporated refrigerant is drawn by the compressor through the reversing valve.

In order to operate the experimental system as a heat pump using engine coolant as a heat source, the refrigerant is directed to the refrigerant/coolant heat exchanger after passing through the TXV2. In this case, the refrigerant absorbs heat from the engine coolant and has a high superheat at the exchanger outlet. In order to test the baseline heating system, the heater core is located downstream of the indoor coil and connected to the proper terminals of the engine thermostat. Further information on the experimental AHP system and its instrumentation can be found in references [6, 7].

The performance parameters of the experimental AHP system can be evaluated by applying the first law of thermodynamics to the system. Using this law for the indoor coil (condenser), the heating capacity of the experimental AHP system can be evaluated from

$$\dot{Q}_{cond} = \dot{m}_r \, (h_{cond,in} - h_{cond,out}) \tag{1}$$

where $\dot{m}_r$ is the refrigerant mass flow rate and h is the enthalpy of the refrigerant.

Assuming that the compressor is adiabatic, the compressor power absorbed by the refrigerant can be obtained from

$$\dot{W}_{comp} = \dot{m}_r \, (h_{comp,out} - h_{comp,in}) \tag{2}$$

The energetic performance of the AHP system is found by evaluating its *COP*, defined as the ratio between the heating capacity and compressor power, i.e.

$$COP = \frac{\dot{Q}_{cond}}{\dot{W}_{comp}} \tag{3}$$

The power output from the engine, which is called the engine brake power, can be determined from the product of the engine torque and engine speed, i.e.

$$\dot{W}_{brake} = T \frac{\pi n}{30} \tag{4}$$

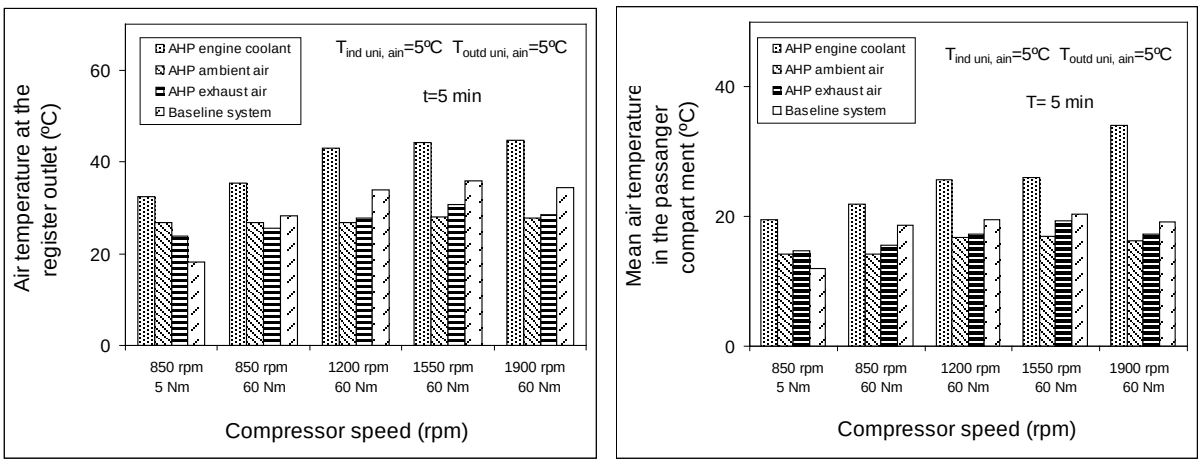
The brake specific fuel consumption of the engine can be evaluated from

$$BSFC = 3600 \frac{\dot{m}_F}{\dot{W}_{brake}} \tag{5}$$

where $\dot{m}_F$ is the fuel consumption rate of the engine.

3. Results

In order to perform the tests, the diesel engine was operated at five different speeds, namely 850, 1200, 1550, 1900 and 2250 rpm. Because the diameters of the crankshaft and compressor pulleys are the same, the engine speed is equal to the compressor speed. The tests at 850 rpm were performed at the dynamometer loads of both 5 Nm (idling operation) and 60 Nm, while tests at other speeds were performed only at the dynamometer load of 60 Nm. In all tests, the air flow rate at the front register outlet was adjusted to its maximum (0.403 m^3s^{-1}). In the tests using ambient air and exhaust gas as a heat source, the air flow rate passing through the outdoor coil was also adjusted to its maximum (0.52 m^3s^{-1}). Before performing the tests, the air temperatures at the inlets of the indoor coil ($T_{ind\ coil,\ ain}$) and outdoor coil ($T_{outd\ coil,\ ain}$) both were fixed to 5 °C. Meanwhile, the relative humidity of the air stream entering the outdoor coil was between 50 and 70%. After these adjustments, the diesel engine was started up and the engine speed along with dynamometer load was rapidly adjusted to the required values. Using data acquired in the test operations, the steady-state performance of the AHP system was evaluated from the Eqs. (1–5), while the air temperature at the outlet of the front register and the mean air temperature in the compartment were considered as the parameters showing the transient behaviour of the system.



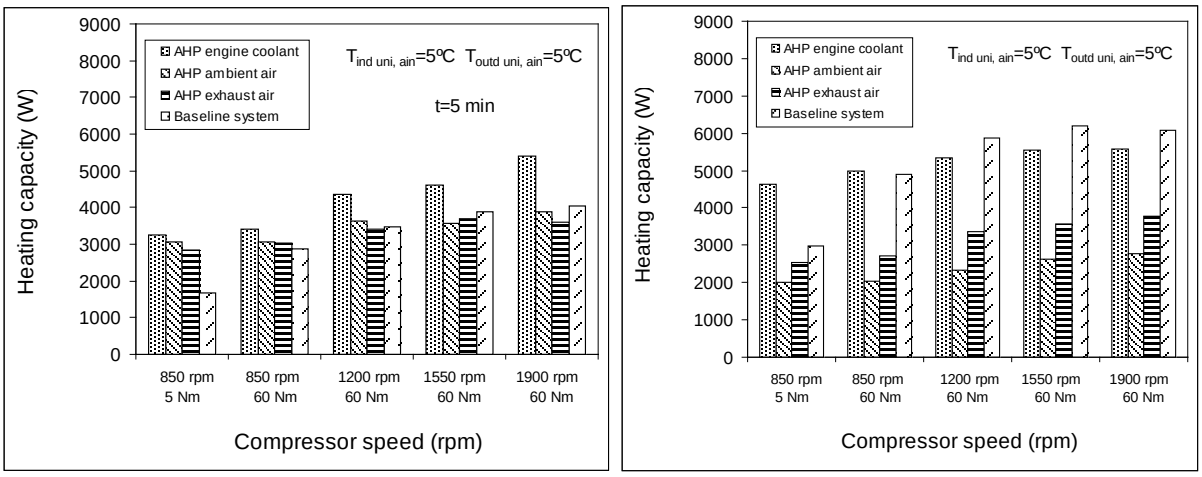
(a) *(b)*

Fig. 2. The change of the air temperature at the compartment front register outlet (a); the change of the mean air temperature in the compartment (b) (both temperatures were recorded at the end of five-minute operation period).

Fig. 2 (a) shows the comparison of the fifth minute air temperatures measured at the front register outlet of the vehicle for the AHP systems and baseline heating system for different compressor speeds and dynamometer loads. It can be seen that the AHP system using engine coolant has higher air temperatures at the front register outlet compared with the AHP systems using ambient air and exhaust gas as well as with the baseline heating system. As the engine coolant temperatures increases, the evaporating temperature also increases, thus yielding higher condensing temperatures and conditioned air temperatures. It is seen that in

the heat pump operations, the air temperature at the front register outlet rises immediately after the compressor is started up. At 850 rpm speed and 5 N m load conditions, the AHP system using engine coolant provides a fifth minute air temperature at the front register outlet of 32°C, while the AHP system using ambient air and exhaust gas yields 26 and 23°C, respectively, and the baseline heating system provides only 18 °C, which is unacceptably low.

The air temperature at the front register outlet rises for all AHP systems when the engine speed and load are increased. In the AHP systems using engine coolant and exhaust gas, this increase is due to the elevated coolant and exhaust gas temperatures, respectively. As the engine speed increases, the refrigerant mass flow rate also increases, thus providing higher heat rejection in the condenser and higher air temperatures at the front register outlet for all AHP systems. Although the AHP system using engine coolant yields higher fifth minute conditioned air temperatures than the baseline heating system, the AHP systems using ambient air and exhaust gas cannot usually provide so high temperatures. Fig. 2 (b) demonstrates the changes of the fifth minute mean air temperatures in the passenger compartment as a function of compressor speed. When the engine speed and load are increased, the mean air temperature in the passenger compartment rises for all AHP systems and the baseline system. For the operations with the engine coolant, this increase is due to the elevated coolant temperature.

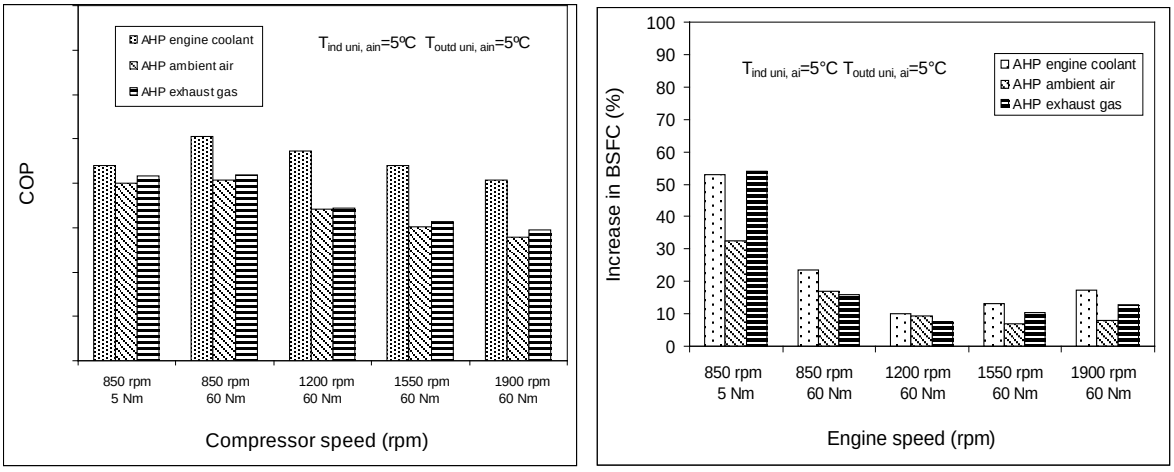


(a) *(b)*

Fig. 3. The change of the heating capacity at the end of five-minute operation period (a); the steady-state heating capacity (b).

Fig. 3 (a) indicates the variations in the fifth minute heating capacity as a function of compressor speed. The heating capacity at the end of the five-minute operation period increases with the compressor speed at a constant engine load. At 60 Nm load conditions, the coolant based AHP system has the highest fifth minute heating capacity at all engine speeds, which is usually followed by other heat pump systems and baseline heating system. Fig. 3 (b) demonstrates that the steady-state heating capacities are usually higher than the fifth-minute ones. In the AHP system with the engine coolant, the refrigerant absorbs a greater amount of heat from the coolant heat exchanger, thereby providing considerably higher heating capacities compared with the AHP system with ambient air or exhaust gas. In the tests performed at 850 rpm and 5 Nm, the coolant based AHP system has the highest steady-state heating capacity, which is followed by the baseline heating system, AHP system using exhaust gas and AHP using ambient air in descending order. However, as the compressor speed is increased, the heating capacity of the baseline heating system gets higher.

Fig. 4(a) indicates the variations in the coefficient of performance of the experimental AHP system as a function of compressor speed based on steady-state data. It is seen that the *COP* for heating decreases by increasing the compressor speed since the compressor power increases faster than the heating capacity does with increasing compressor speed. The AHP system using engine coolant provides the highest *COP* compared with the AHP systems using ambient air and exhaust gas. Fig. 4 (b) shows the impact of the operation of AHP systems on the brake specific fuel consumption at different compressor speeds and engine loads. The *BSFC* increase caused by the AHP operations is very low when the engine speed and load are at high values because most of the power provided by the engine is applied to the dynamometer at these conditions. On the other hand, most of the power provided by the engine is used by the compressor of the AHP system when the engine is operated at low speeds and loads. Therefore, the increase in the *BSFC* due to the operation of the AHP system ranges between 4% and 54% depending on the engine speed and load.



(a) *(b)*

Fig. 4. The change of the COP (a); the increase in the brake specific fuel consumption caused by the operation of the AHP system (b).

4. Discussion and conclusions

Both transient and steady-state performance parameters of an experimental automotive heat pump system charged with R134a and using ambient air, exhaust gas and engine coolant as a heat source have been evaluated. The AHP system was coupled to the passenger compartment of a test vehicle by means of a flexible air duct in order to supply the conditioned air stream to the compartment. The performance of the AHP system for each source was revealed by performing tests at various compressor speeds and engine loads. The performance parameters of the AHP system for each heat source were compared with those of the system using other heat sources and with those of the baseline heating system. Based on experimental data, the heating capacity, coefficient of performance, air temperature at the front register outlet, mean air temperature in the compartment of the test vehicle and the increase in the *BSFC* caused by the operation of the AHP system were presented as a f unction compressor speed. The following conclusions can be drawn from this investigation:

- When the engine is operated at idling conditions (n=850 rpm and T=5 Nm), the AHP system using engine coolant provides the highest steady-state conditioned air temperatures and heating capacities compared with the AHP system using ambient air and exhaust gas and with the baseline heating system.

- On increasing the engine torque and speed, the baseline heating system provides higher heating capacities after the steady-state has been achieved.
- The AHP system using any heat source yields higher conditioned air temperatures and heating capacities than the baseline heating system at the end of five-minute operation period when the engine is operated at the idling conditions.
- Only, the AHP system using engine coolant as a heat source provided a better fifth-minute heating capacity than the baseline heating system at speeds over 850 rpm when the engine load is 60 Nm.
- The AHP system using the engine coolant yields the highest *COP*s, while the AHP system with ambient air results in the lowest ones.
- The AHP system causes an increase in the *BSFC* of the engine within the range of 4–54% depending on the engine speed and load.

Compared with the baseline heating system, when the engine speed and load are at low values, the use of all considered AHP systems at transient phase are advantageous in terms of heating capacity and conditioned air temperature. Because the AHP system using the engine coolant provides higher heating capacities than other alternatives, this system can heat the passenger compartment individually, or it can support the present heating system of the vehicle in expense of increased *BSFC*.

Acknowledgement

The authors would like to thank The Scientific and Technological Research Council of Turkey (TUBITAK) for supporting this study through a Research Project (Grant No. 108M132).

References

[1] E.R. Domitrovic, V.C. Mei, F.C. Chen, Simulation of an automotive heat pump. ASHRAE Transactions, 103, 1997, pp. 291−296.

[2] M. Hosoz, M. Direk, Performance evaluation of an integrated automotive air conditioning and heat pump system. Energy Conversion and Management, 47, 2006, pp. 545−559.

[3] J. Rongstam, F.A. Mingrino, A coolant-based automotive heat pump system, Vehicle Thermal Management Systems Conference (VTMS6) Proceedings, 2003, SAE Paper Code: C599/067/2003.

[4] L.P. Scherer, M. Ghodbane, J.A. Baker, P.S. Kadle, On-vehicle performance comparison of an R-152a and R-134a heat pump system, SAE Technical Papers, 2003, Paper code: 2003-01-0733.

[5] D. Antonijevic, R. Heckt, Heat pump supplemental heating system for motor vehicles, International Journal of Automobile Engineering: Part D, 218, 2004, pp. 1111–1115.

[6] M. Hosoz, M. Direk, K.S. Yigit, M. Canakci, E. Alptekin, A. Turkcan, Design and instrumentation of an automotive heat pump system using ambient air, engine coolant and exhaust gas as a heat source, 16th International Conference on Thermal Engineering and Thermogrammetry (THERMO), 2009, Budapest, Hungary.

[7] M. Hosoz, M. Direk, K.S. Yigit, M. Canakci, A. Turkcan, E. Alptekin, A. Sanli, A.F. Ozguc, Experimental performance of an automotive heat pump system for various heat sources, Congress on Automotive and Transport Engineering (CONAT 2010), 2010, Brasov, Romania, Paper code: CONAT 20104046.

Prospects for eliminating fossil fuels from the electricity and vehicle transport sectors in New Zealand

Jonathan D Leaver[1,*], Luke HT Leaver[2]

[1] *Unitec NZ, Auckland, New Zealand*
[2] *Asia Pacific Energy Research Centre, Tokyo, Japan*
** Corresponding author. Tel: +64 98494180, Fax: +64 98154372, E-mail: jleaver@unitec.ac.nz*

Abstract: New Zealand is a small isolated country in the South Pacific with a population of 4.3 million people that has a strong commitment to reducing greenhouse gas emissions stemming both from its drive for global branding of principal export commodities and a desire to invest in new green technologies. New Zealand's renewable electricity generation reserve using biomass and wind alone is as much as 11 times the 2009 annual electricity demand. In this study the practical limits of fossil fuel reductions in the electricity and road transport sectors of the New Zealand economy are investigated using the multi-region partial equilibrium economic model UniSyD to examine a low carbon scenario in which oil reaches a maximum of US$200/bbl in 2030 in conjunction with a carbon tax of US$200 per tonne of carbon dioxide equivalent. In this scenario biofuel and electric drive vehicles are found to constitute 8% and 36% of the light vehicle fleet in 2050 respectively, with the balance of 56% still being fossil fuel vehicles. Government regulation is likely needed to reduce the proportion of fossil fuel vehicles to below 30% of the total fleet.

Keywords: *Alternative fuel vehicle, battery electric, hydrogen fuel cell, emissions*

1. Introduction

New Zealand is a small isolated country in the South Pacific with a population of 4.3 million people that has a strong commitment to reducing greenhouse gas emissions stemming both from its drive for global branding of principal export commodities and a desire to invest in new green technologies. As part of the commitment to reduce greenhouse gases New Zealand is one of the 187 countries to sign the Kyoto Protocol [1], one of 126 countries that agreed to the Copenhagen Accord [2], and in 2010, joined 28 other countries that have an emissions trading scheme [3].

In 2009 New Zealand produced 72.5% of its electricity from renewable energy [4] with the government aiming to increase this to 90% by 2025 [5]. Based on data from [6] and [7] New Zealand's potential renewable electricity generation reserve using biomass and wind alone is as much as 11 times the 2009 annual electricity demand with this being reduced to a factor of four if a wholesale electricity price limit of 8.4 USc/kWh is imposed. This provides opportunity to consider excluding fossil fuels from the electricity generation and transport sectors except where necessary to provide stability to the national electricity grid.

Studies on the economic impacts of alternative vehicle technologies on the New Zealand economy ([8], [9], [10]) have shown that a hydrogen fuelled fleet offers significant savings over a long range (320 km) battery electric vehicle (BEV) fleet. To achieve up to 80% reductions in greenhouse gas emissions from the transport sector a transition to all-electric vehicles will be necessary. This transition will include the adoption of a range of vehicle technologies [11].

Replacing fossil fuels in the electricity generation mix in New Zealand was shown to be possible for the period 2005-2007 [12]. The key factor in optimizing supply was the effective use of hydro in conjunction with wind. Wind energy spillage, peak load shifting and back-up fossil based peaking plant, were also important elements.

In this study the practical limits of fossil fuel reductions in the electricity and road transport sectors of the New Zealand economy to 2050 are investigated using the multi-region partial equilibrium economic model UniSyD4.4. The term "practical limit" in the context of this study means the utilization of all the available renewable energy resources of New Zealand that are economically viable within the scenario parameters. These resources include hydro, geothermal, wind, biomass (lignocellulose, rape seed) and solar.

2. Methodology

To explore the practical limits of fossil fuel reductions in the electricity and road transport sectors two scenarios were constructed. Each scenario excluded plug-in hybrid vehicles (PHEV) on the basis that these are an intermediate technology between conventional internal combustion engine vehicles (ICEV) and full electric drive vehicles. The scenarios are:

(i) Fossil Future (FF) in which no electric vehicles except hybrids (HEV) compete with the ICEV fleet before 2050. The carbon tax is US$15/t-$CO_{2eq}$ and the oil price rises at 2% per annum in real terms to a maximum of US$120/bbl by 2030.
(ii) Renewables Future (RF) in which BEVs with a 320 km range and HFCVs compete for market share in the vehicle fleet along with HEVs. The carbon tax is US$200/t-$CO_{2eq}$ and the oil price rises at 4.7% per annum in real terms to a maximum of US$200/bbl by 2030. No coal fired fossil fueled electricity generation is permitted.

The scenarios were simulated using the multi-regional partial equilibrium model UniSyD4.4 [8]. This is a system dynamics based model with a high degree of technological specificity in the electricity generation and transport sectors of the New Zealand economy. Each energy sector considers existing technologies and those that are contending to come on-stream to 2050 such as co-generation of hydrogen and electricity from coal or natural gas with sequestration as an option [8]. The model contains about 1150 variables and equilibrates supply and demand in fortnightly time steps in four primary markets in 13 geographic regions of New Zealand. These four markets comprise electricity generation, hydrogen generation, lignocellulose from purpose grown forests and the vehicle fleet. The model incorporates dynamic interactions based on the elasticity of prices with demand. The primary energy resource base for the model consists of hydro, geothermal, wind, biomass (lignocellulose, rape seed), natural gas, coal and solar.

The electricity market regions generate, import and export electricity based on the price of regional production and grid transmission costs. Options for electricity generation or energy saving on a domestic scale include micro-cogeneration of electricity and heat using either hydrogen or natural gas along with rooftop photovoltaics and solar thermal water heating. Temporal fluctuations in wind are neglected.

In the hydrogen market there are four centralised plant types of biomass gasification, coal gasification, large steam methane reforming and coal co-generation of hydrogen and electricity with sequestration of emissions using a solid oxide fuel cell topping cycle. There are five sizes for each plant to match supply with change in demand. Plants in the electricity and hydrogen markets are built by extrapolating demand growth from the previous three years up to four years in the future.

In the lignocellulose market, supply from forests is directly related to the forest residuals and purpose grown forest supply curve based on data from [6]. The biomass cost is determined on a marginal pricing system set in competition between the use of biomass for hydrogen,

bioethanol production and electricity generation. The decision to build a new biomass based plant is determined by the same mechanism as the hydrogen market.

The vehicle market model uses a standard logit choice, also known as a conditional logit model [13] to determine the market share of any particular vehicle technology. The market share is a function of elasticities of fuel cost, purchase price as shown in Fig. 1, maximum range and consumer driving distance.

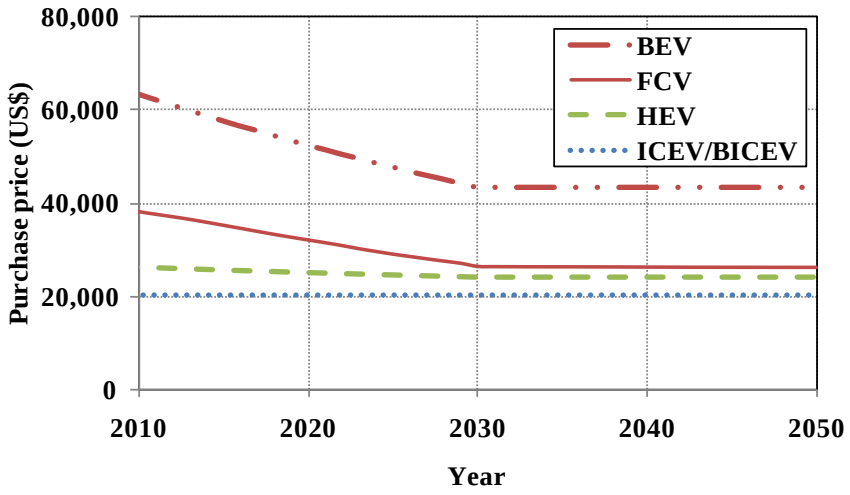


Fig. 1: Purchase price of alternative vehicles.

The standard logit choice model used in this study gives the market share of item *i* (S_i), as a function of the price (p_i), the price elasticity (β_i), and the intrinsic preference parameter (γ_i). The market share, S, is given by [13]:

$$S_i = \frac{e^{(\beta_i p_i - \gamma_i)}}{\sum_j e^{(\beta_j p_j - \gamma_j)}} \quad (1)$$

A significant feature of Fig.1 is that the long term purchase price of BEVs with a 320 km range is likely to be 80% higher than the mean of the other options. In the vehicle market ICEVs, HEVs, FCVs, and BEVs compete for market share. As imported vehicles represented 48.6% of the light fleet in 2009 [14] the imported and New Zealand new light vehicle fleets are modeled separately.

3. Results

The model results for the Fossil Future and Renewables Future scenarios are shown in Figs. 2 and 3 respectively. Under the FF scenario Fig. 2a shows electricity generation from wind increases rapidly after 2025 with the mandated phasing out of fossil fuels. Wind penetration in 2050 is 35% of total generation by 2050 with hydro 38%, geothermal 18% and 9% other renewable generation such as biogasification. In Fig. 2b the electricity price averages about 7.0 USc/kWh after 2030 with the price spike in 2022 reflecting a short term electricity shortage due to the phasing out of coal production that is independent of carbon tax policy. In Fig. 2c, bioethanol production from forest resources provides fuel for 12% of the vehicle fleet by 2050 (Fig. 2e and 2f) with the balance of 88% being fossil fueled. In Fig. 2d GHG emissions decrease by 7% between 2010 and 2050 with a 34% reduction during the period 2020 to 2030 with the reduction in fossil fueled electricity generation. Improving fuel

economy in the vehicle fleet limits increases in GHG emissions for the period 2030 to 2050 to 17%.

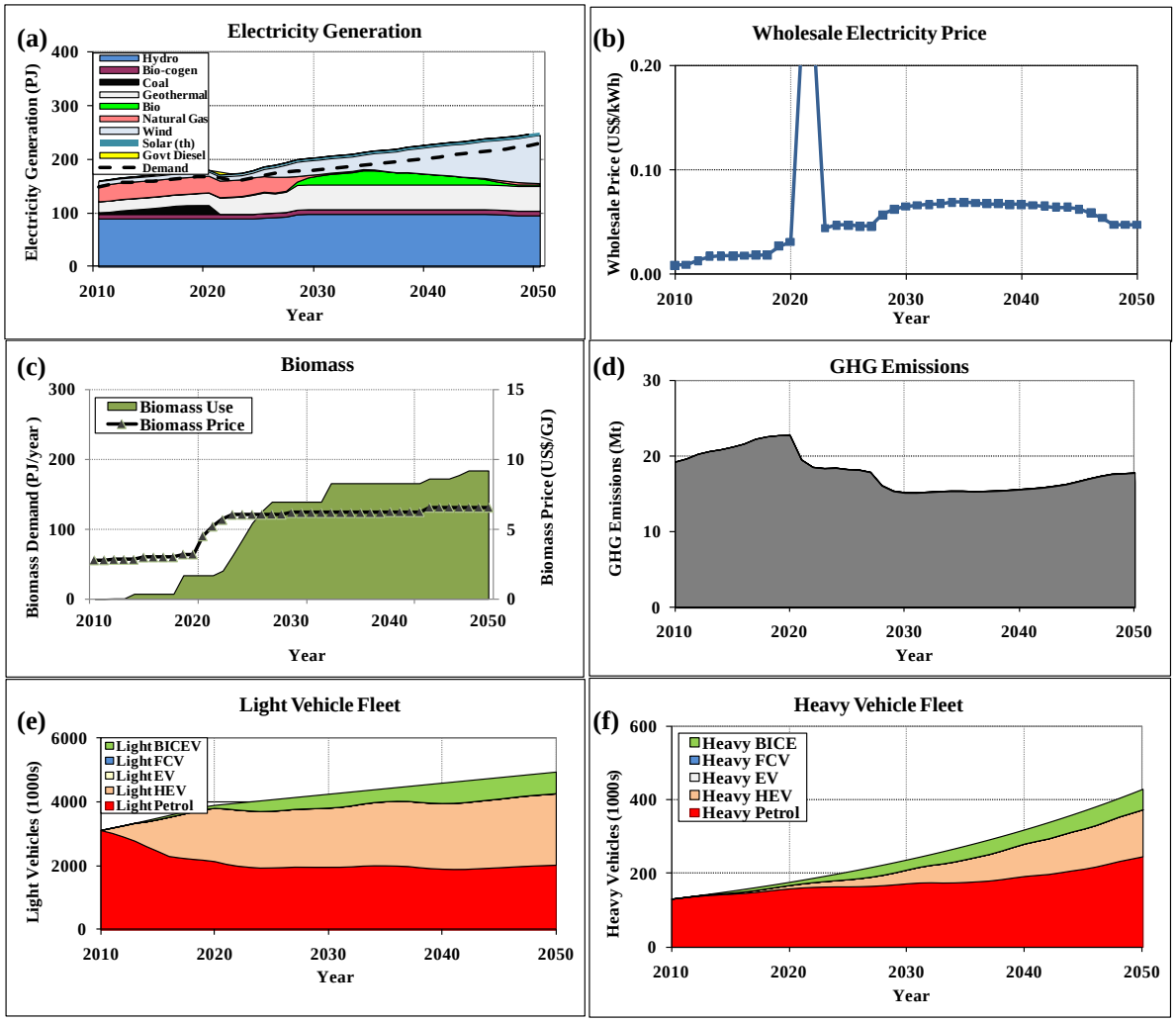


Fig. 2: For the Fossil Futures scenario: (a) Electricity generation profiles. (b) Hydrogen production profiles. (c) Wholesale electricity price. (d) Wholesale hydrogen price. (e) Biomass demand and price. (f) GHG emissions. (g) Light vehicle fleet. (f) Heavy vehicle fleet (g) Fuel economy. (h) Fuel cost per k of travel.

Under the RF scenario in Fig. 3a the high carbon tax eliminates coal fired generation and natural gas generation ceases by 2018. By 2050 the generation profile consists of 41% wind, 36% hydro, 14% geothermal and 9% other renewable generation such as biogasification. Total renewable generation is 97%. In Fig. 3b the electricity price rises to a high of 13 USc/kWh in 2013 with the sudden rise in carbon tax from US$15/t-C to US$200/t-C. Prices average about 7.2 USc/kWh after 2030. In Fig. 3c hydrogen production commences with forecourt electrolysis in 2015 with large scale hydrogen production from biogasification commencing in 2020. Fig. 3d shows that the hydrogen production price is close to US$5.00/kg after 2020. In Fig. 3e biomass use rises sharply from 2016 to 2020 as a primary fuel for hydrogen production by biogasification. In Fig. 3d, GHG emissions decrease by 58% between 2010 and 2050. In Fig. 3g light BICEVs, HFCVs, and EVs constitute 8%, 28% and 8% respectively of the light vehicle fleet in 2050, with the balance of 56% being ICEVs and HEVs. In Fig. 3h, heavy BICEVs and HFCVs constitute 14% and 44% respectively of the heavy vehicle fleet in 2050, with the balance of 42% being ICEVs and HEVs.

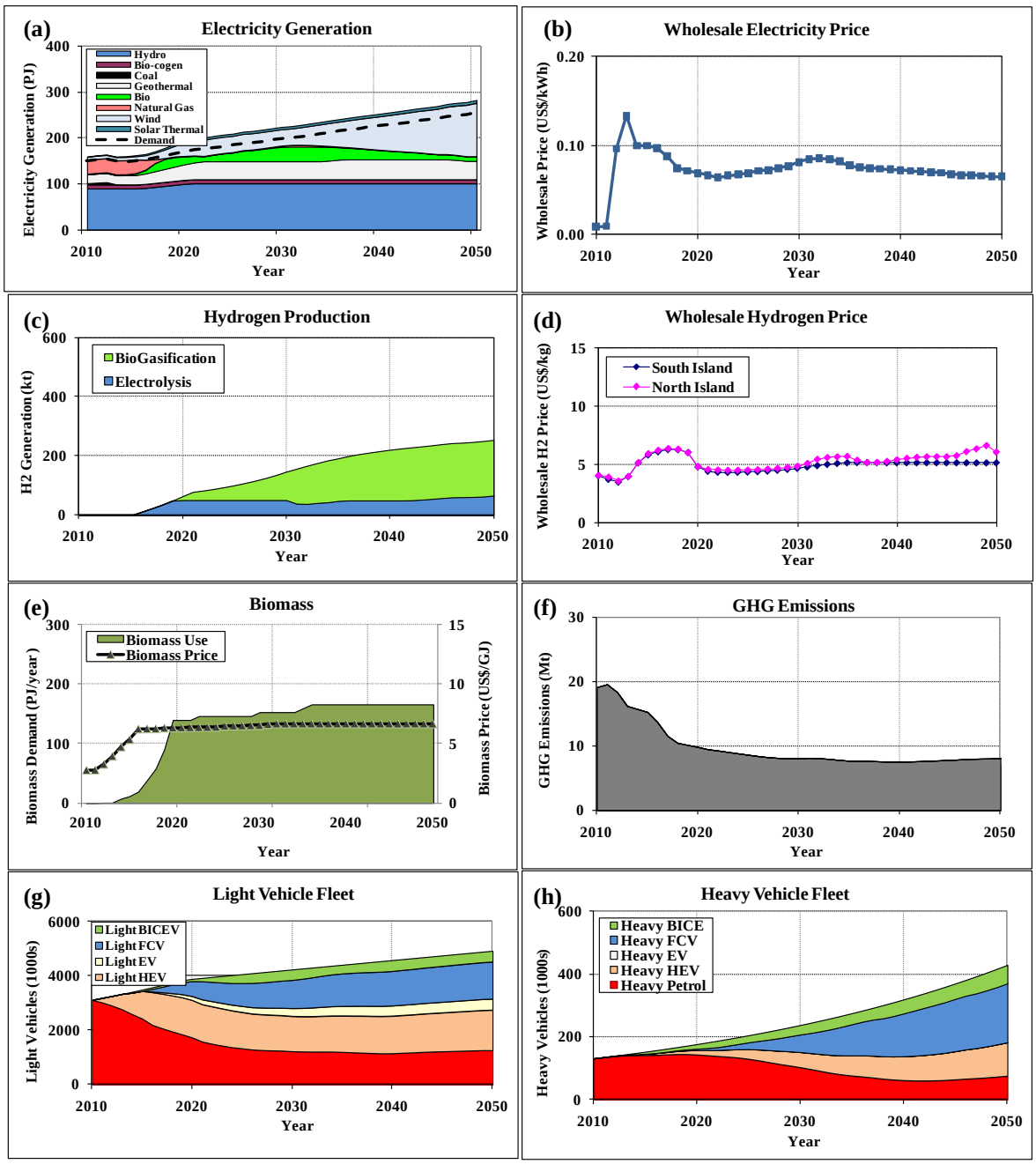


Fig. 3: For the Renewables Future scenario: (a) Electricity generation profiles. (b) Wholesale electricity price. (c) Hydrogen production profiles. (d) Wholesale hydrogen price. (e) Biomass demand and price. (f) GHG emissions. (g) Light vehicle fleet. (f) Heavy vehicle fleet (g) Fuel economy. (h) Fuel cost per k of travel.

4. Discussion

Two primary consequences emerge from a comparison of the Fossil Future and Renewables Future scenarios. Firstly in 2050 in both scenarios all generation excluding backup peak load generation is renewable. The only effect of the high carbon tax in the RF scenario is to reduce geothermal generation by about 4% and replace this with wind. All GHG emissions are from the vehicle fleets. GHG emissions in the RF scenario are 54% less than in the FF

scenario by 2050 which equates to a 54% reduction by weight in fossil vehicle fuel. Secondly the proportion of light ICEVs under the RF scenario of 56% is 32% less than that under the FF scenario of 88%. The fact that the combined penetration of ICEV and HEV in the RF scenario remains high at 56% is a result of the improving fuel economy of ICEVs and HEVs that enhances the competitiveness of these technologies and delays their replacement by all electric BEV and HFCV technologies. Reducing the penetration of ICEV and HEV to less than 30% of the total fleet may require government regulation to encourage adoption of electric vehicles. The primary focus of any regulation should be to reduce the purchase price of electric vehicles with subsidies while recovering the subsidy as a fuel tax. The motive behind this is that purchasers value an incremental reduction in purchase price at twice that of a reduction in running costs [15].

The average electricity price under RF remains stable at about 7.2 USc/kWh despite the increased electricity demand for hydrogen production by electrolysis and subsequent recharging of electric vehicles. This increase in electricity price is buffered by the large wind resource available at less than 8.4 USc/kWh referred to earlier in this study.

Wind penetration in the RF scenario is 41% by 2050 which poses significant issues for the stability of New Zealand's electricity grid. In Denmark the Danish Transmission System Operator is planning for up to 50% wind penetration in the transmission system [16]. However New Zealand cannot import electricity from neighboring countries.

Mason et al. [12] examined wind penetration in the New Zealand electricity system of up to 35% during 2005-2007 when demand totaled 54% of expected demand in 2050. The study concluded that penetration rates of 19% could be achieved by utilizing the existing hydro system to balance periods of low wind generation with almost no reduction in electrical energy from hydro generation.

Wind penetration of 18% has been estimated [17] to incur integration costs of 0.6 USc/kWh as shown in Table 1.

Table 1. Wind integration cost (adapted from [17]).

Year	2010	2020	2030
Installed wind power capacity (MW)	634	2066	3412
Wind energy (PJ)	8.3	24.1	39.1
Wind energy as % of total generation	5	12.5	18
Additional wind integration cost (USc/kWh)	0.14	0.14	0.61

Recent wind integration studies [17, 18] suggest enough standby generation must be available to meet a 'no wind' scenario. Analysis of a 19-year daily synthetic wind speed dataset [19] showed that no wind generation is likely to occur for two days every three years under a geographically diverse wind portfolio. In order to cater for the 'no wind' scenario requirement at 41% wind penetration in 2050, New Zealand will require active demand side management, smart flexible gas contracts and peaking based hydro management coupled with fast start standby thermal generation. This could include remote shut-down of selected hot water heating installations, and short term diversion of electricity and gas supplies from selected large industrial electricity users such as aluminum [20] and methanol [21] production plants. Diversion from large industrial plants has the potential to provide additional backup electricity generation of up to 50% and 66% respectively of predicted wind generation in 2050 under the RF and FF scenarios. Further measures may involve a mixture of pumped hydro storage using off peak electricity, or changing the operating limits of hydro lakes for very short periods.

To ensure grid stability a number of load balancing generation and load shifting options will be needed. Load balancing options would principally include hydro with support from fossil fuelled peaking plants. Load shifting options could include remote shut-down of selected hot water heating installations, pumped hydro storage using off peak electricity, and smart metering that allows real time electricity billing to encourage fast consumer response to electricity price.

This study used an upper bound carbon tax of US$200/t-C to examine renewable energy penetration limits. Marginally lower penetration rates of renewable energy may be possible with a carbon tax of US$100/t-C although a detailed study of this option is outside the scope of this paper.

5. Conclusions

New Zealand's has the potential to achieve over 90% electricity generation from renewables by 2050 but maintaining or exceeding this target to 2050 will require complex integration of peak load backup generation to balance the variability of wind generation. This target is largely independent of the carbon tax due to the large and economically viable wind resource. In the vehicle fleet, in the absence of plug-in hybrid vehicles and without government regulation, 44% of the light vehicle fleet is expected to be electric drive by 2050. The penetration rates of electric vehicles will be enhanced with purchase price subsidies capitalised from fuel taxes.

References

[1] United Nations Framework Convention on Climate Change, Status of Ratification of the Kyoto Protocol, http://unfccc.int/essential_background/kyoto_protocol/status_of_ratification/items/5524.php. Accessed 1 October 2010.

[2] United Nations Framework Convention on Climate Change, Report of the Conference of the Parties on its fifteenth session, held in Copenhagen from 7 to 19 December 2009. Report 3F0C CMCa/rCchP /22001009 /11, 30 March 2010. p. 36.

[3] New Zealand Ministry for the Environment. The New Zealand Emissions Trading Scheme. http://www.climatechange.govt.nz/emissions-trading-scheme/. Accessed 1 October 2010.

[4] New Zealand Ministry of Economic Development, New Zealand Energy Data File: 2009 Calendar Year Edition, ISSN 1177-6676, 2010, p. 174.

[5] New Zealand Ministry of Economic Development, Draft New Zealand Energy Strategy: Developing our energy potential, ISBN 978-0-478-35862-9, 2010, p. 34.

[6] Scion, Bioenergy Options for New Zealand: Situation Analysis, ISBN 0-478-11019-7, 2007, p. 83.

[7] Connell Wagner, Transmission to Enable Renewables: Economic wind resource study, Report 31362/001, 2008, p. 27.

[8] J.D. Leaver, K.T. Gillingham, L. Leaver, Assessment of primary impacts of a hydrogen economy in New Zealand using UniSyD. International Journal of Hydrogen Energy 34 (7), 2009, pp. 2855-2865.

[9] J.D. Leaver, K.T. Gillingham, Economic impact of the integration of alternative vehicle technologies into the New Zealand vehicle fleet. Journal of Cleaner Production, 18, 2010, pp. 908-916.

[10] R. Whitney, T. Clemens, A. Gardiner, J. Leaver, Transitioning to a Hydrogen Economy in New Zealand: An EnergyScape Project, Proc. XXI World Energy Congress, Montreal, 2010, p. 20.

[11] C. Thomas, Transportation options in a carbon-constrained world: Hybrids, plug-in hybrids, biofuels, fuel cell electric vehicles, and battery electric vehicles, International Journal of Hydrogen Energy 34, 2009, pp. 9279-9296.

[12] I.G. Mason, A 100% renewable electricity generation system for New Zealand utilizing hydro, wind, geothermal and biomass resources, Energy Policy, 38, 2010, pp. 3973-3984.

[13] D.L. McFadden, Conditional Logit Analysis of Qualitative Choice Behavior. In P. Zarembka (ed.), Frontiers in Economics, 1973, New York: Academic Press, pp. 105-142.

[14] Ministry of Transport, The New Zealand Vehicle Fleet: Annual Fleet Statistics 2009, ISBN978-0-478-07228-0, 2010, p. 68.

[15] K.E. Train, EM Algorithms for nonparametric estimation of mixing distributions, Journal of Choice Modelling, 1(1), pp. 40-69.

[16] K. Sperling, F. Hvelplund, B. Vad Mathiesen. Evaluation of wind power planning in Denmark: Towards an integrated perspective, Energy (in press), 2010, p.12.

[17] G Strbac, D Pudjianto, A Shakoor, MJ Castro. New Zealand Wind Integration Study. Meridian Energy, April 2008. Accessed 8 November 2010. http://www.meridianenergy.co.nz/NR/rdonlyres/345B3A36-1434-4CAF-95AC-. 10.

[18] B Smith, Wind integration – the long view, Report. The New Zealand Electricity Authority, April 2009.

[19] New Zealand Electricity Commission. Analysis of wind integration – synthetic wind data. April, 2009, http://www.ea.govt.nz/industry/modelling/analysis-of-wind-integration/. Accessed 17 November 2010.

[20] A. Bennett, Meridian boss hails deal with smelter, http://www.nzherald.co.nz/energy/news/article.cfm?c_id=37&objectid=10467340. Accessed 8 November 2010.

[21] Contrafed Publishing Co. Ltd, A train in want of gas, Energy NZ, No.11 2009.

Advanced Research Strategy for Designing the Car of the Future

Konstantinos Gkagkas[1,*], Jonas Ambeck-Madsen[1], Ichiro Sakata[1]

[1] *Toyota Motor Europe NV/SA, Brussels, Belgium*
** Corresponding author. Tel: +32 27123435, Fax: +32 27123325, E-mail:Konstantinos.Gkagkas@toyota-europe.com*

Abstract: This paper describes a novel concept regarding the method for research and development of future vehicles. It is shown that the traditional rate of progress cannot keep up with the increasingly pressing issues of global warming and social sustainability. A new, holistic approach which takes into account the form, operation and social aspects of the future society is suggested. This approach tries to remove the boundaries between different sections of science and also accelerate the rate and speed of adoption of new technologies into the final, mass-produced vehicle. Such an approach can pave the way for the creation of a vehicle that reaches our goal of zero accidents and zero emissions.

Keywords: *Sustainable Transport, Social Sustainability, Future Mobility and Technology*

1. Introduction

The issue of global warming and its relation to human-induced emissions is well known. In 2009, both the European Union and G8 leaders agreed that CO_2 emissions must be cut by 80% by 2050 in order to stabilise the concentration of greenhouse gas (GHG) emissions in the atmosphere at a level of 450 ppm of CO_2 equivalent and keep global warming below the level of 2ºC. Transport accounts for about one-fifth of global energy use and one-quarter of energy-related CO_2 emissions [1]. To achieve the necessary deep cuts in greenhouse gas emission by 2050, transport must play a significant role and achieve 95% decarbonisation. Car ownership worldwide is projected to triple to over two billion by 2050 and, without strong global action, a respective growth of energy use and CO_2 emissions will occur [1]. Fig. 1 shows estimation for EU total greenhouse gas emissions. It can be seen that, following the baseline scenario which already includes large efficiency improvements, especially in industry, the emissions are expected to remain constant. The amount of additional effort that must be put in each sector in order to achieve the necessary emission cuts is clearly visible [2].

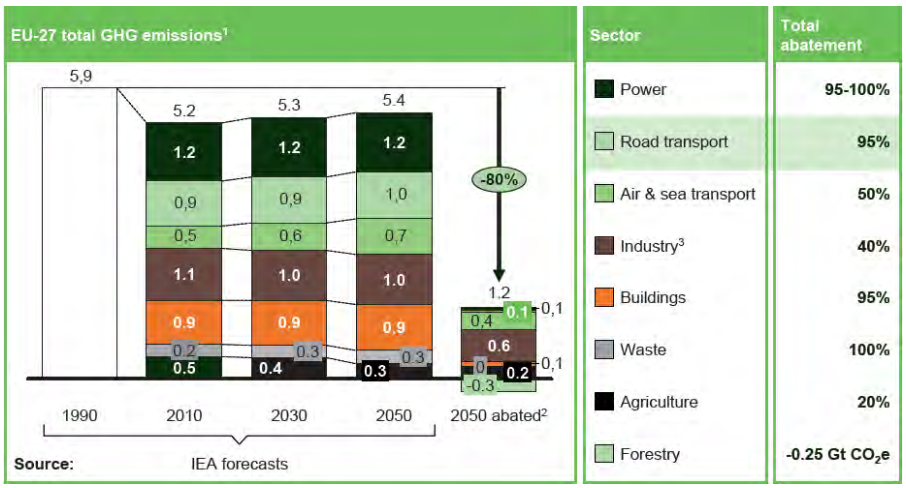


Fig. 1. EU total GHG emissions forecast for 2050 and comparison to target.

Similarly, annual global road-traffic fatalities sum to more than 1 million and injuries to more than 50 millions [3]. Awareness, technological advances and stricter legislation have lead to

the reduction of injuries and fatalities in developed countries as can be seen in Fig. 2; however the increasing level of car adoption, especially in developing countries, means that the global number of fatalities and injuries is likely to increase [3]. The cost of road accidents, in both social and financial terms is not negligible. For example, the cost of fatalities in EU-27 during 2006 corresponded to approximately 2% of the total GDP [4].

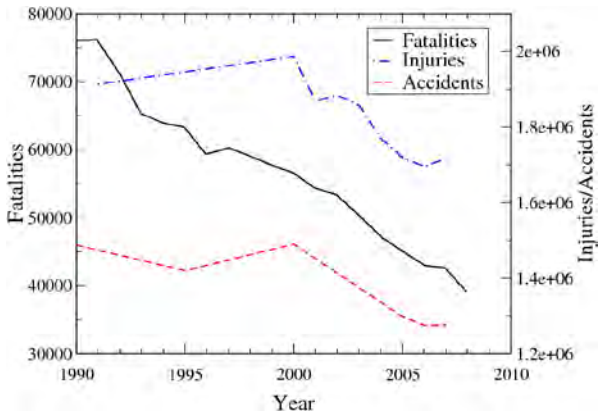


Fig. 2. Road accident statistics for EU-27 [5][6].

Current automotive technology improves at incremental steps, as conventional, long-existing concepts are optimised towards their theoretical limits. Compared to previous decades, current cars provide higher levels of safety and have a similar or lower environmental footprint at the same time. Stricter legislation and industrial competition have supported this trend by leading to the introduction of new or improved technologies in the course of the years. However, growing concerns of the climate change mean that this rate of progress is not viable, as shown in Fig. 1.

The introduction of the mass-produced automobile represented a revolution in affordable, highly flexible mobility and convenience. This flexibility makes its use appropriate especially in cases where large investments in mass transportation are not viable. Its usage has led to significant changes in society and has contributed to economic growth, supporting the growth of small and medium-size businesses over the years. Currently, transport is one of the backbones of European economy, accounting for about 7% of GDP and more than 5% of total employment in the EU. How can we continue to enjoy the benefits of car mobility in a sustainable way, without the associated risks of traffic accidents and accelerated climate change? In the following sections we try to share selected elements of our vision for research carried out in Toyota Motor Europe for creating the future image of automotive transportation, as well as the necessary technologies to make this sustainable. More specifically, in Section 2 we describe our research methodology. In Section 3 we outline our perceived image of the future car and present key technologies that will render it possible. Finally, in Section 4 we summarise our findings.

2. Research strategy

The automobile has evolved over several decades into a practical and reliable product by following a solid approach of thinking and engineering. This traditional approach is starting to become a limitation to the rate of further technology improvement, unable to keep up with the requirement for drastic changes shown in Section 1. The automotive industry is faced with a lot of challenges to deliver innovative products to its customers, and some will likely require a big innovation jump. Currently developed and emerging technologies need to be implemented in new vehicles rapidly, at a rate and on a scale that is unprecedented in the last 40 years of

transport evolution. New technologies that deal with weight reduction, performance optimisation and efficient usage of energy resources need to be developed for reversing the trends of the past decades and achieving our targets in GHG emission cuts, without a negative impact on existing levels of quality and comfort. This will require answers to paradoxical questions such as how can we produce a vehicle which is extremely lightweight and completely safe at the same time? How can we manufacture a vehicle which provides complete freedom and pleasure to the driver and passengers, without any environmental impact? Such questions are indeed paradoxical when following the traditional way of thinking. A fresh, "out of the box" approach is therefore needed to provide answers and solutions which are realistic and feasible in a short timeframe compatible with our extremely challenging targets.

2.1. Limitations of current methodology

Before describing a new research strategy, we first reflect on the more than 100 year long automotive history in order to understand the logic and the potential of the current direction for improving the environmental performance of cars. Fig. 3(a) shows the history of average fuel consumption in Europe and the US for the period 1975-2002. In comparison, fuel consumption of the first mass-produced vehicle, Ford Model T, in 1908, was around 11-18 lt per 100 km [7]. It can be seen that after period of a relatively strong improvement in average fuel economy during the 70s, homologated consumption has roughly stabilised in the US and drops only slowly in EU. This can be explained by Fig. 3(b), which shows the relative evolution of vehicle mass, power and engine size in EU for the same period. It is clear that during the same period, vehicles have become heavier, more powerful and relatively faster. Increases in engine size and vehicle mass can partly be attributed to dieselisation (as diesel vehicles have a lower power/mass ratio), but even so it is evident that the trend for bigger, faster and theoretically safer cars has off-set the gains in efficiency.

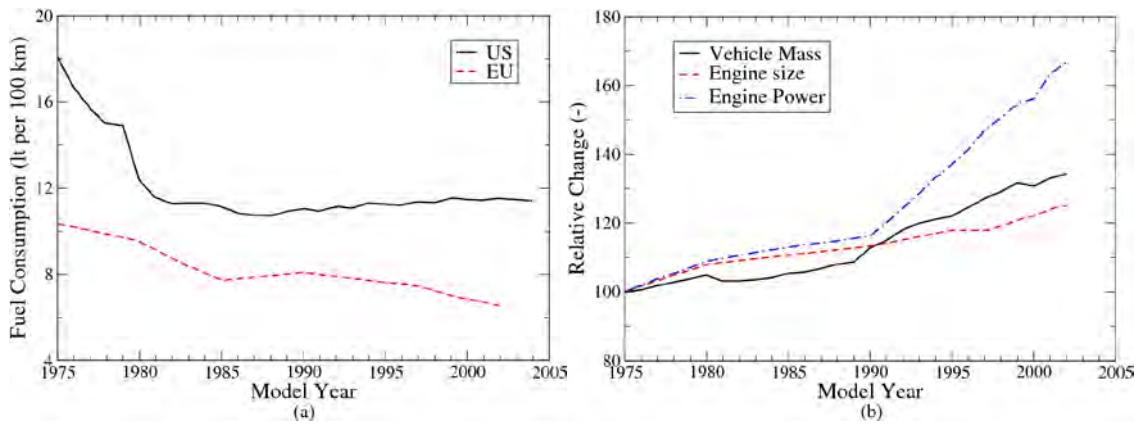


Fig. 3. Evolution of (a) US and EU motor vehicle economy from 1975 to 2003 and (b) average weight, power and engine size of new cars sold in EU from 1975 to 2002[8]

As a second example, Table 1 shows the evolution of a typical vehicle over the last decades. As specifications can vary a lot over different countries and model generations, some typical values are shown, corresponding to a compact sedan vehicle, with comparable acceleration performance. The trend of increasing weight and dimensions is obvious, with a current vehicle being more than 0.5 meters longer, and almost double the weight, compared to 40 years ago. It is also interesting to note that the average fuel consumption has had small fluctuations over the years, with significant reductions being achieved in the last decade, bringing us back to the levels of 1960's. These numbers also verify the findings of the average vehicle evolution trends, with the levels of safety and comfort improving considerably over

the last decades at the expense of potential improvements in performance and fuel consumption.

Table 1. Evolution of Toyota Corolla Sedan typical specifications. Figures obtained from internal TME material.

Year	Length (mm)	Weight (kg)	Engine size (lt)	Power (kW)	Acceleration (s)	Cd (-)	CdA (m^2)	Fuel consumption (lt/100km)
1966	3848	700	1.2	50	13.7		0.6	6.4
1970	3945	801	1.4	63	11.6		0.61	6.82
1974	3995	930	1.6	61	12.6	0.43	0.776	7.92
1979	4048	821	1.5	55	11.5	0.43	0.798	7.51
1983	4135	920	1.6	62	11.6	0.37	0.696	7.22
1987	4191	955	1.6	70	11	0.33	0.62	7.22
1991	4270	1000	1.6	81	10.4		0.631	
1997	4295	1035	1.6	81	10.7	0.33	0.644	7.81
2000	4365	1125	1.6	81	10.3			
2006	4540	1310	1.6	97	10	0.3	0.73	6.4

The design and production of a car is a very challenging exercise, with many contradictory demands. Such demands, limited by existing practices and infrastructure investments, lead invariably to compromises in the final product, and do not allow the full potential of technology to be exploited. The shortcomings of this approach can also be noticed in the current development of new generation, alternative drive-train vehicles, which are essentially developed on the platform of traditional ICE cars with a direct replacement of engine and the addition of energy storage or conversion devices in space which could opportunistically be used for the comfort of the passengers or as optimised shape for drag reduction. Similarly, the current strategy of tackling the possible dangers that inherently quiet electric vehicles may pose to pedestrians by adding artificial noise is another example of lack of “new thinking” in what could be a chance for a significant reduction in urban noise pollution.

2.2. New approach

It becomes clear from subsection 2.1 that in order to induce the required paradigm shift, a new way of thinking and performing research is necessary. Since several years, we try to seek inspiration in all kinds of science around us. Such inclusive thinking incorporates cutting edge research in engineering. We can find interesting concepts in the work of several research groups. A recent example is the development of a battery which can also be used as a structural material [9], therefore removing significant duplication of the weight. Research from NASA has led to a self-sustainable marine vehicle [10], while Lotus Engineering has recently shown that a significant weight reduction can be achieved using relatively standard technologies and with a minimum impact in cost [11]. However, our truly multidisciplinary research approach extends beyond the conventional limits of engineering to concepts not directly related to vehicles, such as biology and social sciences, and can provide new seeds of technology which are not limited by topic and therefore also not in scope. In nature we observe many truly amazing technology-like functions, and we have long been looking here for inspiration to solve some of our fundamental engineering challenges related to both vehicle safety and sustainable energy efficiency. Another pillar of our approach is that we take into account the future society structure and operation and thus our real target becomes to increase the efficiency of the whole system, rather than a single component, as done traditionally. In such a holistic approach, we consider the automobile not as an individual unit,

but as a living part of a bigger organism. This way, many of the existing obstacles can be overcome and a higher rate of development can be achieved.

In addition, we consider practical aspects such as the cost of new technology, investments in infrastructure, local energy resources availability, as well as human aspirations and market diversity. Sustainable mobility, apart from dealing with environmental and energy issues, must also satisfy the individual customer needs, meaning that it must maintain or improve upon the current acceptable levels of performance, safety, comfort and practicality. It must also respond and adapt to changes in lifestyle, such as urbanisation and network connectivity, converting such changes into opportunities for further improvements. Finally, it must maintain and extend the personal freedom of the driver and the passengers, keeping the aforementioned benefits of private transportation, in a socially and environmentally responsible manner.

Such a quest for a potentially sustainable automotive transportation technology, as described in Section 1, is slowly starting to gain traction globally. A recent example is the LA Auto Show Design Challenge which has been providing a platform for presenting new ideas over the past seven years. A different theme, relevant to different aspects of future car usage, is employed each year, and some interesting ideas can already be seen [12].

3. Image of the sustainable vehicle

Following the approach described in Section 2, we estimate that the amount of energy needed for car transportation by 2050 is possible to be one order of magnitude lower than current levels and the emitted greenhouse gases close, if not equal, to zero. By removing inefficiencies in all the subsystems and introducing new technology concepts, we are aiming at creating a vehicle which can propel itself without any fossil fuel derived energy support while maintaining the current levels of vehicle performance and occupants comfort.

3.1. Evolving society

The large-scale availability of affordable liquid fuels has essentially sparked a modern industrial revolution over the 20th century and shaped the transportation sector. Today transport is at a transition point, as it is starting to become a victim of its own success. The genesis of our image for the future car should therefore be viewed in the context of its existence inside the future society. A society which we believe will be characterised by the lack in cheap resources, growing levels of population and urbanisation. This future society will be more extrovert and will strive to remove inefficiencies following a global optimisation approach. In such an environment, information will constantly be transferred and exchanged, allowing each subsystem to automatically adapt its operation in order to support a smooth global operation. New information technologies, providing immense wealth of information, are already starting to move in this direction [13].

Apart from the information exchange, which is necessary for a smooth coexistence of the different structures in a society, another important concept which needs to be materialised is that of energy exchange. By this, we mean the constant adaptation of energy resources used, in order to achieve the most efficient energy production, as well as the constant energy re-usage process, during which energy is converted into different forms without loss. The successful combination of energy and information exchange processes will ensure the achievement of such a smart and self-regulating entity.

3.2. Shaping the future car

In such exchanging society, different means of transportation have their own role to play. We believe that the desire for the pleasure, freedom and practicality of personal mobility will not be eclipsed, and therefore the personal car will continue to have an important role. By actively taking advantage of opportunities presented in the future society, automotive transportation can adapt and be optimised in order to achieve successful merging and co-existence in the daily life of its citizens.

A self-sustainable vehicle has, first of all, to remove the past inefficiencies. Fig. 4 shows the energy losses in two usual driving scenarios, according to [14]. It can be seen that the energy which finally results in the actual mobility of a conventional car corresponds to less than 20% of the available energy from the fuel. A lot of new technologies aim at reducing or removing such energy losses, although, arguably, the most significant of these losses is inherent to the historical operation of the thermal engine and is the hardest to tackle. Another source of inefficiency is the mass of the vehicle itself and the associated inertial effects. As shown in Section 2, the improvements in engine technology have been offset by the weight increase over the last decades, with the fuel economy not being able to improve as drastically as it could. It is highly paradoxical that a vehicle of more than 1000kgs is needed for the transportation of an 80kg person. It is clear that different technology is required in the design of future vehicles.

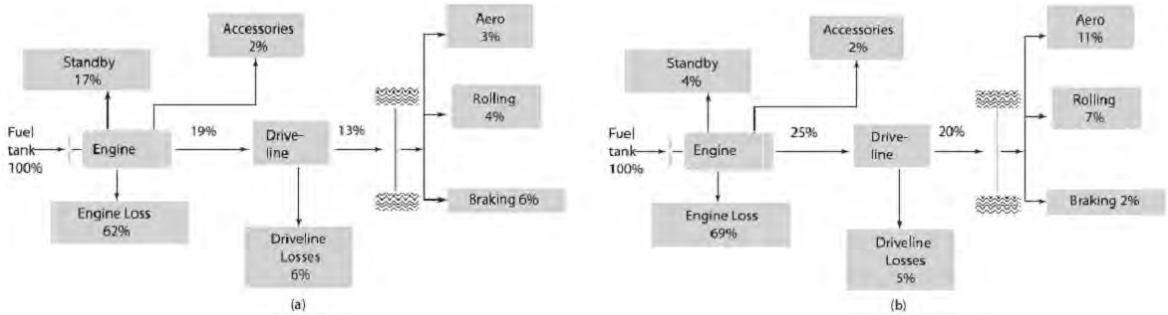


Fig. 4. Energy dissipation in (a) urban and (b) highway driving [14]

Completely in line with our image of the future society, the future vehicle takes advantage of all the available information and energy forms in order to maximise its potential and optimise its operation. Like the combined intelligence of a school of fish that travel together in a way that offers them safety and ensures the minimum drag during their movement in the water, our future vehicle can communicate with its surroundings and adapt its operation in a way that removes the danger of accidents, while respecting the individuality and the preferences of the driver. Moreover, this communication and adaptation allows the usage and re-usage of the available energy in the best possible way without losses, but with continuous transformation from one form to another.

A significant gain can be achieved by reducing the mass of the vehicle considerably. We envisage a five-fold reduction in this sector. A combination of ideas will be necessary for this target to be achieved. First of all, the novel intelligent safety systems will ensure that it is possible to avoid any dangerous situation at all times, and therefore reduce the reliance on increasingly stronger individual vehicle structures, which can be parallelised more to the sturdiness of an elephant, rather than the elegance and nimbleness of a bird. Then, a new generation of materials, inspired by nature and based on simple, cheap building blocks which gain their strength by their internal microstructure will allow the creation of vehicles which

are more in line with their natural surroundings. The human organism consists of materials which do not necessarily have significant individual strength or potential. However, due to their relative organisation and control under powerful sensory and cognitive skills, they can be protected by catastrophic damage and are capable of achieving comparatively amazing results. Finally, the integration of multiple functions in fewer structures or components can remove unnecessary weight.

Such optimizations can significantly reduce the amount of energy which is necessary for mobility. This has initially a positive impact on the rate of existing resource depletion. More importantly, though, it can enable an era of desired self-sustainability, where the naturally occurring energy streams can be harvested and exchanged efficiently, thus minimising the link to fossil fuel consumption.

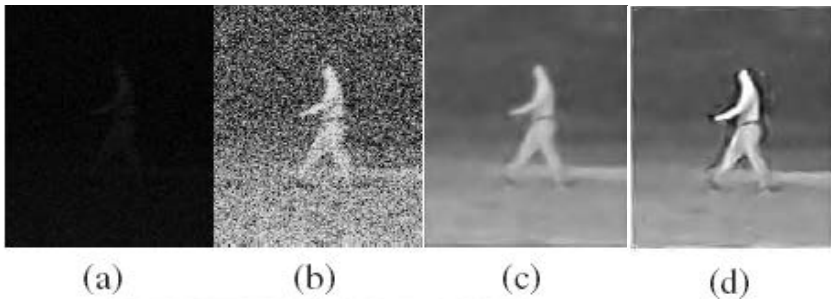


Fig. 5. Example of image enhancement by novel night vision algorithm: (a) Original frame. (b) Tone mapped version. (c) After noise reduction. (d) After noise reduction with sharpening.[15]

Fragments of such ambitious thinking can already be seen in cutting edge research. An example of research is a novel night vision system, inspired by the eyes of nocturnal insects [15]. The algorithm developed in this project was born from understanding how an insect can hunt for food which is beautifully coloured flowers at night, navigating with its normal eyes. A sample result is shown in Fig. 5. Whereas traditional technologies might saturate in terms of performance, results obtained from such a holistic research framework can have the potential to leap-frog beyond current frontiers.

3.3. Contribution of the engineer

We are faced with the tough challenge of adapting this totally new knowledge back into existing systems and applications of our industry, to fully measure and evaluate its true potential, but it is a challenge which we are working hard to overcome. To do so, first we try to play a binding role by bringing different kinds of science together and removing the borders between them. Secondly, we try to identify the potential and feasibility of each technology, and quickly pursue its development and application into the final product through interaction with development, production engineers, marketing etc. For successful guidance in such an approach, we set a clear future target, like the one we are presenting in the current paper. We believe, based on our experience from ongoing projects, that this concept will allow a revolutionary design and integration of subsystems, paving the way to radically new implementations.

4. Summary

We have a dream of zero accidents and zero emissions for our future car. The pressing sustainability issues mean that our dream is relevant more than ever. In this paper, we propose the development of technologies which support the process of exchanging energy and information as a way to reach this target. By such challenging of traditional thinking we aim

to spark innovation for game-changing technologies, leading to a truly sustainable mobility solution, from both an environmental and social point of view.

References

[1] International Energy Agency, Transport Energy and CO2: Moving towards Sustainability, OECD Publishing, 2009, pp. 29 – 41.

[2] EIA (US Department of Energy, Energy Information Administration), International Energy Outlook 2010, DOE/EIA-0484(2010), 2010, p. 6.

[3] World Health Organization, World Report on road traffic injury prevention, Geneva, 2004, pp. 33-38.

[4] Commission of the European Communities, Impact Assessment of the Communication "Keep Europe Moving". Sustainable mobility for our continent. Mid-term review of the European Commission's 2001 Transport White Paper, Brussels, 2006, p. 74.

[5] Commission of the European Communities, A Sustainable Future for Transport: Towards an integrated, technology-led and user friendly system, Brussels, 2009.

[6] C. Nicodème, K. Diamandouros, J. Luiz Diez, I. Fusco, M. L. Lorente Miñarro, European Statistics 2010, European Union Road Federation, 2010, pp. 50-55.

[7] Media.ford.com, Model T Facts, Retrieved 2010-12-15, Available at: <http://media.ford.com/article_display.cfm?article_id=858>.

[8] T. Zachariadis, On the Baseline Evolution of Automobile Fuel Economy in Europe, Energy Policy 34, 2006, pp. 1773-1785.

[9] Imperial College London, Cars of the future could be powered by their bodywork thanks to new battery technology, 2010, Available at: <http://www3.imperial.ac.uk/newsandeventspggrp/imperialcollege/newssummary/news_5-2-2010-10-26-39>.

[10] NASA/Jet Propulsion Laboratory, NASA demonstrates novel ocean-powered underwater vehicle, ScienceDaily, 8 April 2010. Available at: <http://www.sciencedaily.com-/releases/2010/04/100405142152.htm>.

[11] Lotus Engineering, Lotus Engineering Study Concludes Vehicle Mass Improvement of 38% by 2020 vs a Conventional Current Vehicle Can Be Achieved at Only 3% Cost, Green Car Congress, 27 April 2010, Available at: <http://www.greencarcongress.com/2010/04/lotus-20100427.html>

[12] LA Auto Show, Design Challenge 1000lb car, 2010, Available at: <http://www.laautoshow.com/DC10/>

[13] C. Heipke, Crowdsourcing geospatial data, ISPRS Journal of Photogrammetry and Remote Sensing 65, 2010, pp. 550-557.

[14] The National Academies, Tires and Passenger Vehicle Fuel Economy, Transportation Research Board Washington D.C., 2006, p. 40.

[15] H. Malm, M. Oskarsson, P. Clarberg, J. Hasselgren, C. Lejdfors, E. Warrant, Adaptive enhancement and noise reduction in very low light-level video, IEEE 11th International Conference on Computer Vision, 2007

Electric Vehicle with Charging Facility in Motion using Wind Energy

S.M. Ferdous[2,*], Walid Bin Khaled[1], Benozir Ahmed[2], Sayedus Salehin[1], Enaiyat Ghani Ovy[1]

[1] *Department of Mechanical & Chemical Engineering*
Islamic University of Technology, Board Bazar, Gazipur-1704, BANGLADESH
[2] *Department of Electrical & Electronic Engineering*
Islamic University of Technology, Board Bazar, Gazipur-1704, BANGLADESH
* *Corresponding author. Tel: +8801912669030, E-mail: tanzir68@gmail.com*

Abstract: The main disadvantage of Electric Vehicle is the lack of capability of storing sufficient energy to run the vehicle for a long time. The energy storage capacity of battery used in electric vehicle is very low compare to conventional fuels used in modern automobiles. The operation, performance and efficiency of motor driven electric vehicles are much better than engine driven vehicles, at the same time electric vehicles are very much environment friendly. Still electric vehicles are falling behind in the automobile industries due to the problem of storage of energy. This paper is based on the concept of charging the batteries of an electric vehicle when it is in motion or propelling. This may be done by using the energy of wind which is caused by the relative motion between the vehicle and the wind surrounding it. Wind turbines can be mounted on the body structure of the vehicle to generate electricity in such a way that it must not create any additional drag force (rather than the existing drag force due to frontal area and skin friction) upon the vehicle. An elaborate aerodynamic analysis of the structure of the vehicle along with the flow pattern and wind turbine is presented in the paper. Some techniques and methods are proposed to minimize the drag imposed by the introduction of the turbines as much as possible. Optimum values of different design parameters and rated velocity of the vehicle are of prime concern. With this concept it may be possible to increase the mileage of an electric vehicle up to 20%-25% and it will also save the charging time of the battery to a great extent. Flow pattern over the vehicle is simulated using software called ANSYS CFX.

Keywords: *Electric Vehicle, Wind Energy, ANSYS-CFX, Wind Turbine, Drag Reduction*

1. Introduction

When a vehicle moves it experience wind resistance which are classified in two different forms- frictional drag and form drag. Frictional drag arises due to viscosity of air and form drag arises due to variation of air pressure in the front and rear side of the vehicle [1]. As the vehicle moves forward, it lefts the air stream behind. A turbulence or disturbance is created on the wind when a vehicle moves through it. If stationary wind turbines are placed near the road then energy can be extracted from the wind stream generated due to the movement of the vehicle. Such a study had been carried out in University of Arizona by a group of students. If it is possible to capture those wind streams within the vehicle itself then it can be used to recover some of energy that has been used to overcome the form drag (aerodynamic drag) of the vehicle. If this wind energy is used to extract some power in such a way that it does not create any component of force or thrust opposite to the direction of the propulsion of the vehicle, then this gained energy can be used to produce electricity to charge up the battery of the electric vehicle itself. At the same time drag can be expected to be reduced by passing this air to the rear side (Low pressure side) of the vehicle. Air stream sliding over the body of the vehicle cannot enter into the rear side due to vortex shedding [1]. If air streams are allowed to flow in this region by any means then the form drag will be reduced by some amount and at the same time it may be possible to generate electricity using the kinetic energy of wind. Several studies had been carried out in this field but none of them are proved to be scientific. During the Second World War, wind turbines are used in submarines to charge up the batteries when they remained static and float in the water. At present it is also common to use turbines in ships, caravans and vehicles when they are parked. But to extract power from a

moving vehicle is quite difficult as the turbine will act as a load for the vehicle. Most of the design showed that the turbines are placed over the vehicle roof without considering the fact that it will impose an additional load for the vehicle and on the other hand no measures had been taken to reduce it. A design by Rory Handel and Maxx Bricklin showed that it has four tactically placed air intakes which will channel the air flow over the car's body towards the turbine. No such detailed design was available.

In this paper the topic is dealt by considering all the scientific facts and laws of energy conversion. A new approach is proposed and simulation of the design is carried out to analyze the behavior of the model. Some theoretical formulas have been used for the purpose of calculations.

2. Basic Theory

It is assumed that the vehicle is moving in a calm and steady wind stream with zero wind velocity. If the vehicle is moving at a constant speed of 15 m/s (54 km/h), then we can think a wind stream with15 m/s is flowing around the vehicle. Normally this wind will cause a drag force which is opposite to the direction of the propulsion of the vehicle. At constant speed (zero acceleration) the energy requirements to move the vehicle forward are –To overcome the frictional force (rolling resistance of road) and to overcome wind resistance [1]. At this Condition, if the air stream flowing around the vehicle (which was not interacting with the vehicle previously) is allowed to enter inside and let it flow down to the rear side; then it may be possible to use these air streams to generate power. The vehicle has already interacted with this wind and it deflects the stream of wind at the two sides of it by stagnation at the front. This is the energy that had been lost from the vehicle to overcome the aerodynamic resistant. Now if these stream generated by the interaction of the wind and vehicle is captured within the vehicle in such a way that it would not impose an additional drag at the direction of propulsion of the vehicle, some of the energy can be recovered and fed back to the battery by means of conventional energy conversion processes. Placing a wind turbine can serve the purpose. At the same time it will help to increase the pressure at the back side (according to Bernoulii's equation pressure will be increased if velocity is decreased and velocity will be reduced at the back side of the turbine after energy extraction) which will reduce the drag force that existed before with the conventional design of the vehicle. So, vortex shedding will be reduced at the rear side. For this it is necessary to modify the design of a vehicle which gives provision of air flow through the vehicle. On the other hand positioning of the turbines will also be important because they must be placed in such a way that they do not impose or create any additional drag on the vehicle. Symmetrical positioning of the turbine can do the trick as the thrust acting on the turbines will cancel each other.

3. Design and Modeling

We can consider a vehicle which is redesigned to allow airflow and wind turbine can be set up to extract energy. Wind turbines are set in parallel with the flow of air. This set up will not create any additional thrust at the direction of propulsion. Two basic equations will be needed to explain the air flow and power extraction.
The air flow through the vehicle is given by, [2]

$$Q = C_v A v \qquad (1)$$

Where, Q = flow rate in cubic meter per second.
C_v = opening effectiveness

[Value for C_v is 0.5 - 0.6 for perpendicular flow and 0.25 – 0.35 for skewed flow] [2]
A = Area in square meter
v = air velocity in m/s
This equation (1) will determine the amount of air flow through the vehicle inlet area.
Output power from a wind turbine is given by [4],

$$P_T = 0.5\, C_P\, \rho\, Q\, v^2 \qquad (2)$$

Where,

P_T = Power output from the turbine in watt.
C_p = Power co-efficient
(Assuming, C_p = 0.4 for the design) [4]
ρ = air density; 1.225 kg/m^3.
Q = air flow in m^3/s.
v = air velocity in m/s.

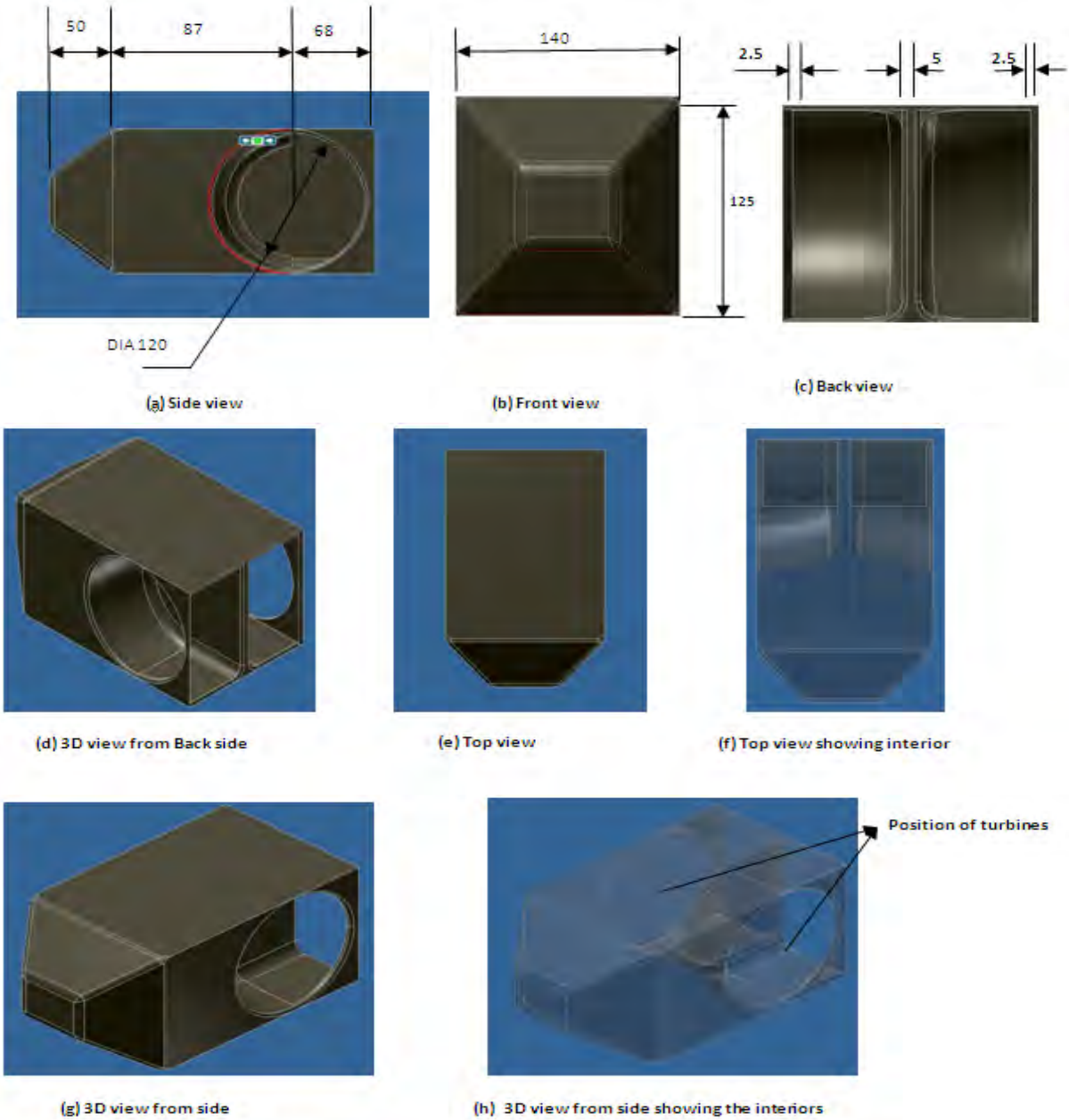


Fig. 1. 3D and isometric views of the model. The diameter of the turbine is 120 cm which is placed at the rear side of the vehicle. The length of the vehicle is 255 cm. All dimensions in the diagram are in centimeters.

In conventional vehicle air cannot go to rear side of the vehicle due to presence of boundary layers and vortex shedding. If a high-pressure and a low-pressure region can be connected via a neutral zone, then air can flow in between these pressure regions. Our design will allow the air to flow in this manner. The detail designs with dimensions are shown in the fig.1.

The vehicle is run by a 1.5 KW DC motor which has five 12V, 120 A-h D.C battery to supply power to the motor. The vehicle has to move at a velocity of 54 km/h i.e.15 m/s. The design of the vehicle is shown here with all dimensions. In this design the wind turbines are set in such a way so that the axial thrusts on the turbines are 180° apart to each other which results in the cancellation of two thrusts. In this way this symmetrical positioning of the turbines will create no additional drag component over the vehicle. Placing the turbines on the top will increase the frontal area as well as the drag acting on the vehicle. So that approach is not scientific. Rather some solar panels can be placed on the top to aid the recharging of the vehicle, both in motion and parked position. In addition if the vehicle is parked in a place where the wind velocity is above cut in speed then it is possible to charge the vehicle and thus it could aid the total charging system and hence charging time can be reduced.

4. Wind turbine

The wind turbine chosen for power generation has the features stated bellow [5] –

- Two blades (for low solidity).
- Horizontal axis.
- Lift type.
- High lift to drag ratio with efficiency ranging from 0.4 to 0.45. They need a relatively high tip speed ratio ($\lambda = \omega R / v_w$). For our design we have chosen $\lambda = 6$. For this value of λ it can be assumed that the value of C_p will be 0.4 to 0.45.

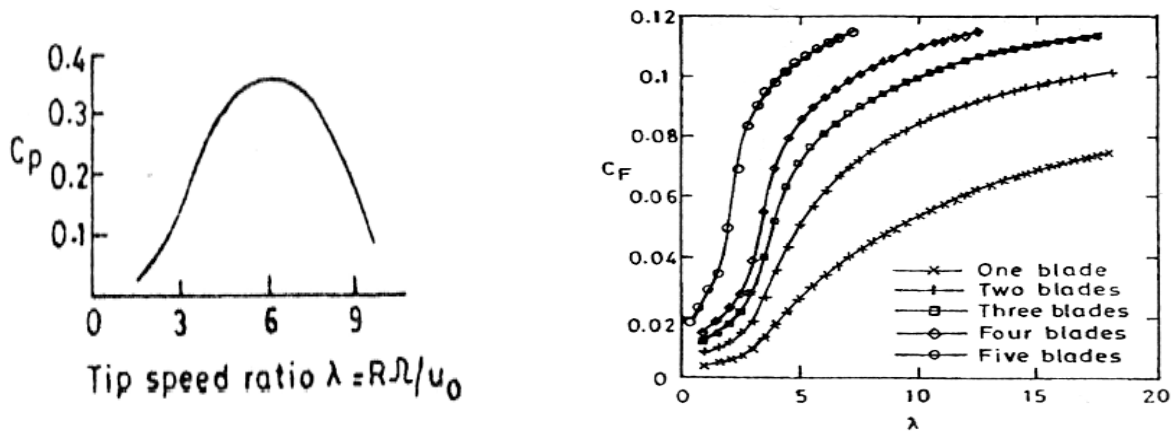


Fig. 2: Power Coefficient and Axial Thrust Coefficient for HAWT [6].

From $C_p - \lambda$ and $C_F - \lambda$ curve we can see $C_p = 0.4$ and $C_F = 0.055$ [6]

Where,

C_F = axial thrust co-efficient.

So, $C_p/C_F \approx 7$

This implies that as at perfect dynamic matching generated power will be greater than the power spend due to thrust. In other words the generated power by a turbine will be greater

than the thrust acting on the blade as an aerofoil section has high lift to drag ratio. On the other hand, turbines are placed in parallel to the flow rather than perpendicular to the flow.

5. Generator

We want to use an A.C. generator with 3-Φ windings with increased no. of poles. The poles will be permanent magnets and the no. of poles will be 8.

$\lambda = 6 = \omega R / v_w$; $\omega = 6\, v_w/R = \frac{6 \times 15}{0.6} = 150$ rad/s; R.P.M, $N = \frac{60 \times \omega}{2\pi} = 1433.12$;

This eliminates the need of a gear box in the system.
We shall use a three phase A.C. to D.C. converter to charge the batteries. Cúk converter is used to give a constant 60V at the output. The current of the converter will vary with the variation of the speed of the vehicle or the r.p.m of the turbine keeping the terminal voltage fixed.

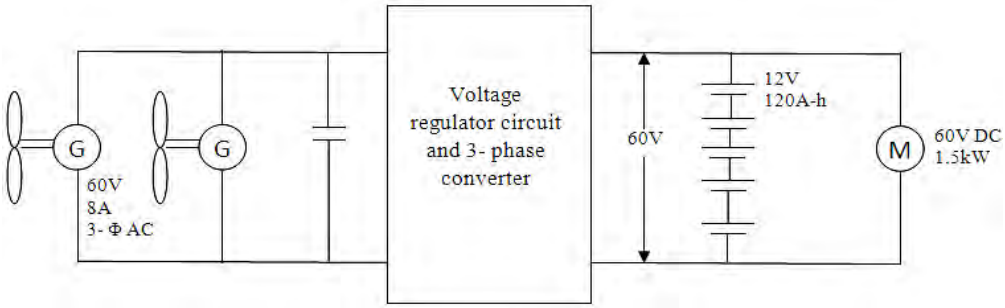


Fig. 2. Charging and control circuit of the battery. 3Φ windings are used to reduce the ripples. A motor control circuit can be used to control the motor and it will also introduce the provision of Regenerative Braking. Simple Power diodes can be used for designing the converter circuit. The cut-in velocity (minimum wind velocity to generate power) of the turbines is 5m/s.

6. Calculation

Using equation (1) we can calculate the amount of air flow,
$Q = C_v\, A\, v = 0.25 \times 0.8 \times 1.131 \times 15 \times 2 = 6.8\ m^3/s$

Here, $A = \pi r^2 = 3.1416 \times 0.6^2 = 1.131\ m^2$

$v = 54$ kmph $= 15$m/s

Here multiplier of C_v is 0.8 as ratio of the inlet and outlet area is 1.38. C_v is chosen as 0.25 as it is a skewed flow [3].

So, Power, $P_w = \frac{1}{2} \rho\, Q\, v^2 = \frac{1}{2} \times 1.2 \times 6.8 \times 15 = 918$ W

Assuming, $C_p = 0.4$ Then we have,

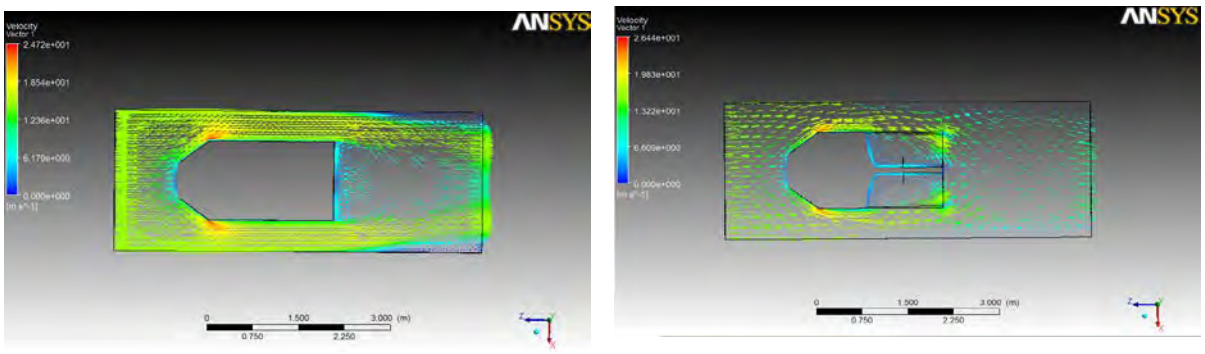
$P_T = 918 \times 0.4 = 367.2\ W \approx 360\ W$

So, each turbine will produce a power of 180 W. This much power will be fed back to the battery when it is moving at a constant velocity of 15m/s.

So increase in mileages = (1500-1140)/1500 x 100% = 24%. This is due to the feeding back of some of the energy captured by the turbine which is spend to overcome the aerodynamic drag. That means the turbines are capturing some fractions of the energy which has already been spend by the vehicle to overcome the aerodynamic drag.

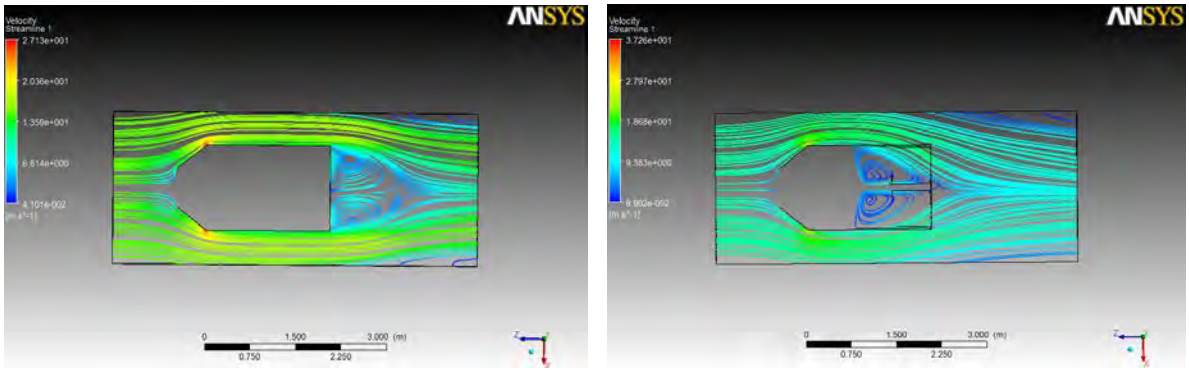
7. Simulation Result

The Flow pattern over the model is simulated using ANSYS CFX. Two models had been chosen for simulation. One is the conventional design and another one is modified design which includes turbines on the vehicle. Using the simulation result the pressure difference and force acting in the direction of flow (i.e. the thrust acting against the direction of propulsion) is calculated. The simulation results are shown and analyzed in the following figures.



(a) Conventional vehicle model without ducts for turbine **(b) Modified vehicle model with ducts for turbine**

Fig. 3. Flow pattern around the vehicle using the velocity vectors. Wind is entering inside the vehicle and going out. Energy will be extracted from this flow.



(a) Conventional vehicle model without ducts for turbine **(b) Modified vehicle model with ducts for turbine**

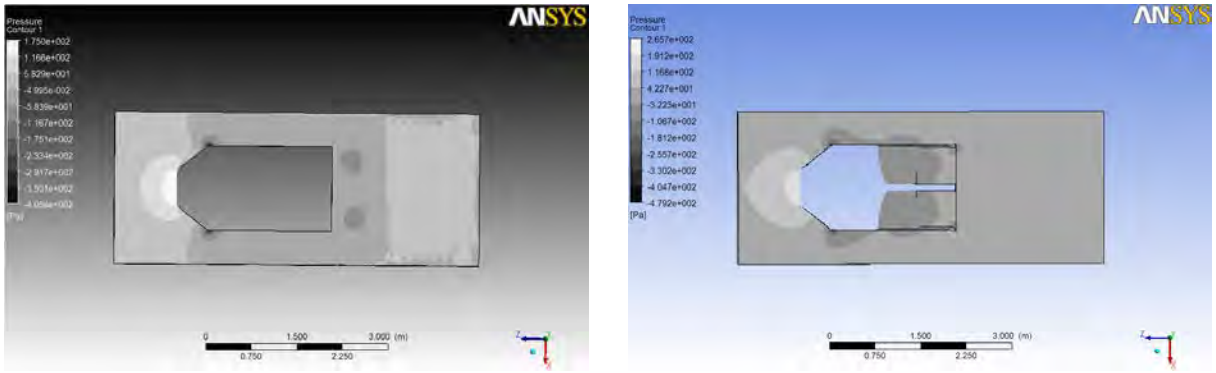
Fig. 4. Streamline of flow over the two different models of the vehicle. It may be noted that the vortexes on the modified design is reduced. On the other hand an additional propulsive thrust can be obtained as the streamlines are leaving the vehicle.

Analyzing figure 3 and 4, it can be seen that the wake region and vortexes are reduced for the modified design which implies that the force (form drag) that existed before is reduced. So it can be concluded that the prediction of flow through the duct and hence reduction of drag should be possible with this modified design. On the other hand, turbines can be placed in these ducts for extraction of some of the kinetic energy contained in the flow. The inlet and outlet pressure along with forces of these two models found from simulation are tabulated in Table 1.

Table 1. Simulation results for pressure and forces

Comparison Parameters	Conventional Design		Modified Design with ducts for turbine	
	Inlet	Outlet	Inlet	Outlet
Pressure(Pa)	2.29185	-1.24196	2.28742	0.240414
Force(Drag)(N)	45.9144	6.5354	15.5202	11.605

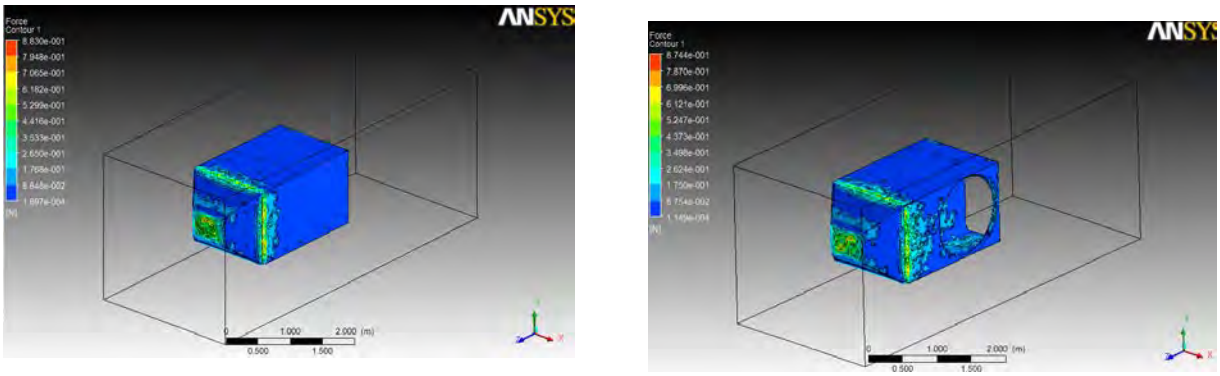
Table.1 shows the plane force and pressure over the two designs have been tabulated. The variation of force and pressure are identical for the both designs, but there are variations in the magnitudes of the parameters. The outlet pressure is increased for the modified design which indicates a reduction in form drag.



.

(a) Conventional vehicle model without ducts for turbine **(b) Modified vehicle model with ducts for turbine**

Fig. 5. Pressure contour around the two models.These figures indicate that the variation of pressure and generation of force due to this pressure variation would be identical but opposite in direction. This symmetry in the design should cancel out the additional thrust crated on the vehicle.



(a) Conventional vehicle model without ducts for turbine **(b) Modified vehicle model with ducts for turbine**

Fig. 6. Force contour showing force exerted by the air on the two vehicles which are almost same.

Further analyzing the diagrams we can see (from Fig.3) that the thrust will not be on the axis of the turbine. That means an additional drag force will arise due to placement of the turbines. We predicted that the thrust will be 180 degree apart and hence cancel out each other. But

from velocity vectors we found that the thrusts are not fully at opposite rather they are in a skewed direction. The horizontal components will cancel each other but the vertical components will impose a resultant force. Hence a resultant thrust will be generated against the direction of propulsion on the turbine.

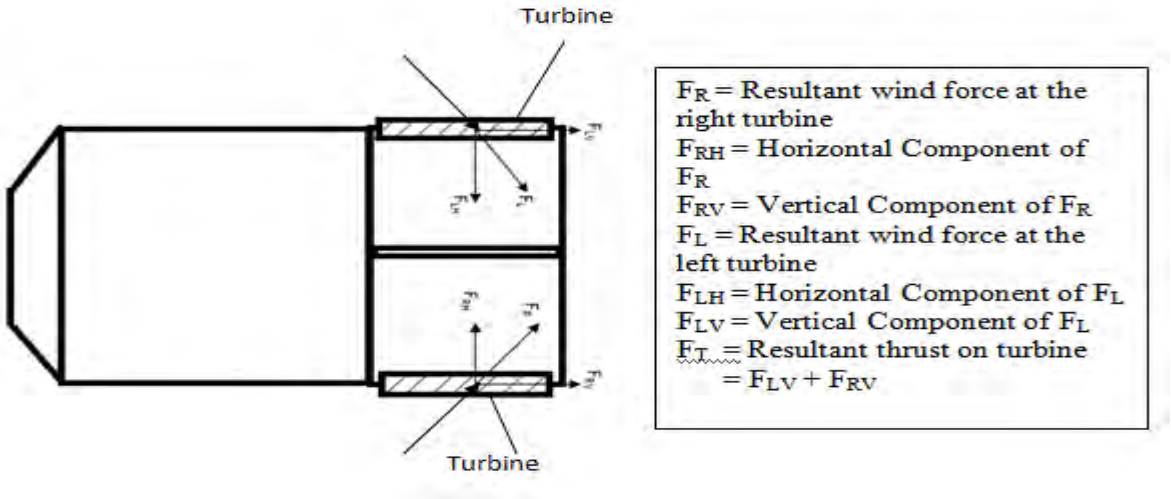


Fig. 8 : Resultant thrust generated on the turbines due to air flow through the ducts.

8. Conclusion

The prime concern with this model is that whether this design will create any additional resistive force components opposite to the direction of the propulsion. It has been found by the simulation that a drag will be induced due to addition of turbine. Overall simulation result along with graphs from Fig.3 will suggest that the overall effect will be same which means the modified design will experience almost same amount of drag compare to the conventional one. But the addition of turbines may give the provision of capturing some energy which will offer some benefits for the vehicle as discussed earlier. A physical structure of the design should be used to carry out wind tunnel tests which are yet to be done. At first the system may resembles with perpetual motion. But a careful observation may indicate that the system is trying to recover some of the energy spend to overcome the aerodynamic drag. The concept of placing symmetrical turbines is presented for the very first time by us. We believe it requires more research and elaborate analysis which we expect to continue in future.

References

[1] Thomas D. Gillespie, “Fundamentals of Vehicle Dynamics”, Society of Automotive Inc.

[2] Terry S. Boutet,” Controlling Air Movements- A Manual for Builders and Architects”, McGraw- Hill Book Company.

[3] Victor Olgyay, “Design with climate”, Princeton University Press, 1963, p.104

[4] Godfrey Boyle, “Renewable Energy- Power for a sustainable future”, Oxford University Press.

[5] Dr. Amalesh Chandra Mandal, Dr. Md. Quamrul Islam, “Aerodynamics and Design of Wind Turbines”, Published by BUET.

[6] G.N.Tewari, A.K. Bansal, “Renewable Energy Resources”, Narosa Publishing House.

[7] Martin O.L. Hansen, “Aerodynamics of Wind Turbines”, Earthscan, London.

[8] Bent Sorensen, “Renewable Energy” Academic Press, USA.

[9] Mukund R. Patel, “Wind and Solar Power Systems” CRC Press, USA.

[10] John D. Anderson, “Fundamentals of Aerodynamics”, McGraw Hill Book Company.

Whole-system Optimisation for Carbon Footprints Reduction of Corn Bioethanol

Andrea Zamboni[1], Nilay Shah[2], Fabrizio Bezzo[1,*]

[1] *CAPE-Lab, Dipartimento di Principi e Impianti di Ingegneria Chimica, Università di Padova,via Marzolo 9, 35131, Padova, Italy*
[2] *CPSE – Centre for Process Systems Engineering, Imperial College London, South Kensington Campus, SW7 2AZ London, UK*
** Corresponding author. Tel: +39 0498275468, Fax: +46 0498276461, E-mail: fabrizio.bezzo@unipd.it*

Abstract: Whether biofuels production from starchy biomass can actually be environmentally is still an open question. A modelling approach for strategic systems design combining lifecycle analysis (LCA) and supply chain optimisation (SCO) analysis can significantly contribute to clarify the question. Here we discuss the possibility of managing and optimising the biomass cultivation stage and its integration through the entire production network in order to tune the environmental performance of bioethanol production. The design task is addressed through a quantitative modelling tool, which aims at steering crop management towards the best fertiliser usage and distillers dried grains with solubles (DDGS) end-use in order to ensure optimal whole system performance in terms of both profit and greenhouse gas (GHG) emissions.

Results shows how a crop management strategy devised from a whole systems perspective can significantly contribute to reduce biofuels carbon footprints. In particular, it is observed that through whole systems optimisation, the GHG emissions of so-called first-generation biofuels can approach those associated with second generation ones.

Keywords: *Bioethanol, Whole system optimisation, Supply chain, GHG emissions*

1. Introduction

Over the past years biofuels for transport have been acknowledged as one of the key issues within the world energy agenda. Among the alternatives, bioethanol through first generation productions was first hailed as the most appropriate solution aiming at a partial substitution of oil-based fuels. Although the initial verve, founded on the potential economic benefits as well as on the energy supply security ensured by a broad range of suitable feedstock (i.e sugar cane and starchy biomass), the first generation pathway has recently known oppositions by both the public opinion and part of the academic community. The core of the question revolves around ever increasing doubts on whether bioethanol could effectively ensure the expected potential in terms of global warming mitigation, particularly when the energy vector derives from the conversion of starchy biomass [1,2].

This did contribute to heat up an already existing debate on the actual carbon footprints of these productions. Most of the studies addressing the question [1-6] state that ethanol derived from starchy biomass can actually contribute to a partial oil displacement [3,4,6], although the effective environmental impact tightly relates to the technological and geographical context in which the system performs, and to specific details in the operation of the overall supply chain. For example, GHG emissions from corn-based ethanol production can be estimated between 3% and 86% [5] lower than the emissions from gasoline production, depending on how the ethanol is produced. This large variability is mainly related to biomass production conditions: climate, properties of soil, cropping management and cultivation practice in general [3] can generally contribute to about 45% of the overall GHG emissions [7]. The raw nerve is represented by mineral fertilisers (mainly nitrogen-based ones) as their extensive application in biomass cultivation stage is the primary source of GHG such as nitrous oxide (N_2O) [8]. On the other hand, nitrogen dosage would also entail *direct effects* on biomass production

parameters and, as a consequence, *indirect effects* on the subsequent stages of the network itself. Technically, increasing the nitrogen input per unit of cultivated land causes: *i*. a direct increase in the corn yield, and, indirectly, in the ethanol yield; *ii*. a direct increase in the yield of grain protein to the detriment of starch content of corn grains, and, indirectly, improving the by-products (i.e. DDGS) yield to the detriment of the ethanol yield; *iii*. a direct increase in costs related to fertilisers, but indirectly to reducing operating overheads as an indirect consequence of the potential increase in both ethanol and DDGS yield; *iv*. an indirect increase of the total global warming impact due to greater GHG emissions coming from both fertiliser production and N_2O release from soil.

Another important aspect of the lifecycle emissions relates to the end-use of valuable sub-products (e.g. heat and power or DDGS), and the assumptions about the products that they displace (e.g. coal-derived energy and soya meal) [7]. This is influenced by nitrogen application, too: the potential increase in by-products yield coming from the over-dosage of mineral fertiliser can cause an indirect increase in emission credits coming from products displacement.

All these issues evidence a conflicting situation which cannot be cleared up by means of a mere heuristic evaluation of the pros and cons of fertiliser application. Thus, it raises the obvious need for a fully integrated analysis embodying all those issues (i.e. global warming mitigation together with economic and financial feasibility) that may help defining a more comprehensive and quantitative view of the interactions along the entire biofuels production system so as to assist both crop and fuel producers and, most importantly, policy makers in their strategic decisions. To the best of our knowledge, no analysis has so far been presenting the adoption of modelling tools to *optimise* the overall bioethanol supply chain by taking into account the entire set of production stages in the supply chain including biomass cultivation.

Some of our prior works have addressed the development of optimisation tools linking LCA and SCO models (i.e. Multi-objective Mixed-Integer Linear Programming - MoMILP), and specifically devised for the optimisation of both the environmental and economic performance of biofuels production [7]. Here we discuss the possibility of managing and optimising the biomass cultivation stage, too, and its integration within a quantitative MoMILP model which aims at tuning the environmental performance of bioethanol production so as to identify strategies for deep, system-wide reductions of GHG emissions.

Eventually, the emerging biomass-based ethanol production in Italy is assessed as a real world case study to demonstrate the actual approach capabilities in steering the crop management toward the best overall nitrogen fertiliser usage and DDGS end-use technical choice ensuring best whole-system performance in terms of both profit and GHG emissions.

2. Methods and modelling assumptions

The modelling framework here described is conceived as an optimisation problem in which the production chain is required to comply with both profit maximisation and impact minimisation criteria. Key components of the optimisation problem include biomass production response to nitrogen dosage (yields, costs, etc); biofuel production facilities capital and operating costs as a function of biomass characteristics; transport logistics costs and emissions; environmental burdens of biomass and biofuel production as a function of nitrogen dosage as well as of the DDGS end-use options; and energy market features (energy purchase prices and green credits).

The objective is to determine the optimal system configuration in terms of financial profitability (NPV) and GHG emissions. Therefore, key variables to be optimised include nitrogen dosage over the biomass crop field, DDGS end-use solution, system financial performance over a 10 years horizon and system impact on global warming.

The problem is referred to a fixed land surface (30,000 ha) fully cultivated to supply the biomass needs of a unique production plant of flexible capacity, anyway ranging within a consistent interval, namely 80–120 kt/y.

2.1. Mathematical formulation

The mathematical formulation of the proposed framework is based on t he modelling approaches adopted in the design of multi-echelon SCs [9,10], by also introducing multi-period features to address the financial analysis (which is performed over a 10-years time horizon).

2.1.1. Objective functions

The first objective considered is the NPV (Obj_{NPV} [€]) of the business to be established. This imposes the maximisation of profit-related indexes, and hence the Obj_{NPV} value is required to be written in its negative form:

$$Obj_{NPV} = -NPV = FCC - DNI \tag{1.a}$$

where FCC [€] are the facility capital costs and DNI [€] represents the discounted net incomes.

The second objective is to minimise the total daily GHG impact (Obj_{TDI} [kg CO_2-eq/d]) resulting from the SC operation. Thus, the definition of Obj_{TDI} needs to consider each life cycle stage contribution, as expressed by the following equation:

$$Obj_{TDI} = \sum_s I_s \tag{1.b}$$

where I_s [kg CO_2-eq/d] are the stage-related environmental impacts resulting from the operation of the single stage s.

2.1.2. Economics

The FCC term accounts for the capital investment required to establish a new fuel conversion facility. However, this model allows for the choice between two different technological options according to the two mentioned options proposed for DDGS use: k =1, which involves the standard conversion technology in which DDGS is processed as a s imple by-product to be sold to the animal fodder market; or k = 2 which envisages the construction of a CHP station fuelled by DDGS to produce heat and electricity.

According to this, FCC can be calculated by alternatively assigning the capital investment value (CI_k [€]) corresponding to the technological features adopted, as expressed by:

$$FCC = \sum_{n,k} CI_k \cdot W_{n,k} \tag{2}$$

where $W_{n,k}$ is the binary decision variable controlling whether to establish a production facility of type k when a nitrogen dosage n is applied: a value of 1 allows for the construction of the plant type k, otherwise 0 is assigned.

The discounted net incomes *DNI* is defined as the sum over the 10 year operating period of the annual profit before taxes (*PBT* [€/y]) plus the annual depreciation charge related to the capital investment (*D* [€/y]) minus the taxation charge for each year *t* (*TAX* [€/y]), as expressed by the following equation:

$$DNI = \sum_t (PBT - TAX + D) \cdot \varepsilon_t \quad (3)$$

All the terms on the right hand side of Eq. (3) have been discounted through the application of a discount factor (ε_t) defined as [11].

The profit before taxes *PBT* represents the gross annual profit and has been defined as the difference between the total annual revenues *TAR* [€/y] and the total operating costs *OC* [€/y] for year *t* minus the depreciation charge *D*. Accordingly:

$$PBT = TAR - OC - D \quad (4)$$

TAR represents the annual incomes which depend on both ethanol and DDGS sales:

$$TAR = MPe \cdot \sum_{n,k} Pe_{n,k} + \sum_{n,k} Pd_{n,k} \cdot MPd_{n,k} \cdot \omega_k \quad (5)$$

where *MPe* is the bioethanol market price (set equal to 709 €/t according to [12]); $Pe_{n,k}$ [t/y] and $Pd_{n,k}$ represent, respectively, the ethanol and DDGS production rate related to plant technology *k* when a nitrogen dosage *n* is applied to crop biomass; $MPd_{n,k}$ is the DDGS market value and depends on the DDGS end-use solution *k*. When DDGS is used as soy-meal substitute in the animal fodder market (*k* = 1), $MPd_{n,1}$ is the market price that also depends on the nitrogen dosage *n*. On the other hand, if power generation is chosen as the end-use option (*k* = 2), $MPd_{n,2}$ identifies the average market price per unit of electric energy sold to the grid. This does not depend on the nitrogen dosage *n* in any case. This modelling solution also requires the application of a conversion factor, $\omega_{n,k}$, to quantify the amount of by-product produced per unit of DDGS. Thus, when power generation is chosen as end-use solution (*k* = 2), $\omega_{n,2}$ [$kWh_e/t_{10\%m}$] identifies the amount of energy that can be sold to the grid per unit of DDGS produced. On the other hand, when DDGS is used as a soy-meal substitute in the animal feed market (*k* = 1), the amount of by-product to be sold should be equal to the overall DDGS production. In order to comply with Eq. (5), $\omega_{n,1}$ [t/t] has been set equal to 1.

OC is given by the sum of the annual operating costs over the entire supply chain. This has to account for the contribution of all the supply stages (*s*), i.e. biomass production (BP), ethanol and DDGS production (EP) and transports (for biomass, BT, and ethanol, ET), minus the by-products allocation credits (BC). Accordingly:

$$OC = \sum_{n,k} \begin{bmatrix} (Pb_{n,k} \cdot UPCb_n)_{BP} + (Pe_{n,k} \cdot UPCe_n)_{EP} + (UTCb \cdot Pb_{n,k})_{BT} \\ + (UTCe \cdot Pe_{n,k})_{ET} - (Pe_{n,k} \cdot UCRd_{n,k})_B \end{bmatrix} \quad (6)$$

where $Pb_{n,k}$ represents the biomass production rate supplying a conversion plant of type *k* when a nitrogen dosage *n* is applied to crop fields, $UPCb_n$ [€/t_{DM}] and $UPCe_n$ [€/t] are respectively the unit production costs for biomass and ethanol, *UTCb* [€/t_{DM}] and *UTCe* [€/t] define the unit transport costs for biomass and ethanol respectively, and $UCRd_{n,k}$ is the cost reduction per unit of DDGS used as a valuable alternative *k* and produced when a nitrogen dosage *n* is applied.

The last factor defining *PBT* in Eq. (4) is the depreciation charge *D* evaluated by simply dividing the total capital investment (*FCC*) by 10 (thus assuming a constant depreciation strategy).

2.1.3. Environmental impact

The definition of stage-related environmental impacts I_s [kg CO_2-eq/d] resulting from the operation of the single stage *s* is calculated as follows:

$$I_s = \sum_{n,k} f_{s,n,k} \cdot F_{n,k} \quad \forall s \tag{7}$$

where $f_{s,n,k}$ is the a g lobal emission factor representing the carbon dioxide emissions equivalent at stage *s* for technology *k* and nitrogen dosage *n* per unit of reference flow; whereas $F_{n,k}$ uniquely defines the reference flows for each individual life cycle stage and expresses them explicitly as a function of the design variable controlling the optimisation problem. In this problem $Pb_{n,k}$ represents the reference flow for biomass production and biomass transport, $Pe_{n,k}$ for ethanol production and ethanol transport, whereas $Pd_{n,k}$ refers to the emissions credits.

2.1.4. Logical constraints and mass balances

All the variables defined in the above are linked to the specific SC features through the definition of a set of constraints that must be satisfied in each of the SC stages.
A set of relations is formulated to constrain the goods production rate together with the binary variables. In particular, $Pb_{n,k}$ is the dominant production variable and is defined as follows:

$$Pb_{n,k} = LA \cdot GY_n \cdot W_{n,k} \quad \forall n,k \tag{8}$$

where *LA* [ha] is the land availability (30,000 ha, as declared in the previous section) and GY_n [t_{DM}/ha] the grain yield per hectare when a nitrogen dosage *n* is applied.

Once the biomass production is quantified, the ethanol and DDGS production rates can be derived by simply applying a specific conversion factor. Accordingly:

$$Pe_{n,k} = Pb_{n,k} \cdot \gamma_n \text{ and } Pd_{n,k} = Pb_{n,k} \cdot \delta_n \quad \forall n,k \tag{9}$$

where γ_n [$t_{biofuel}/t_{biomass}$] and δ_n [$t_{10\%m}/t_{biomass}$] are respectively the alcohol and DDGS yields when biomass is cropped by applying a nitrogen dosage *n*.

2.2. Response curves

The definition of the variables response to nitrogen dosage is based on the comprehensive work by Smith et al. [13], which, however, refers to wheat. Since no complete sets of data could be retrieved on corn, it was decided to tune up the wheat data set to corn cultivations on the few data available. Correlations for wheat reported in [13] have been used to define both the graphical and the mathematical dependence of corn grain yield (*GY*), grain protein content (*PY*), DDGS yield (*DDGSY*) and alcohol yield (*EY*) on nitrogen dosage (*ND*). The entire set of model parameters and their inherent dependence on ni trogen application have to be estimated on the basis of these response curves. Because we wish to maintain model linearity, we use a piecewise linear dependence of key variables on ni trogen dosage. The nitrogen dosage variable is discretised into a number (=12) of intervals *n* (25 kg_N/ha of extension). Note that in general climatic and land characteristics may have an impact on the actual crop

response to nitrogen dosage and this should be taken into account when applying the methodology.

The technological related parameters, i.e. GY_n, δ_n, γ_n and μ_n, have been directly obtained by the corresponding response functions. In particular, μ_n is the soy-meal replacement factor representing the amount of soy-meal that can be replaced by DDGS. Thus, in this work we do not assume an allocation by energy on DDGS, but a substitution as fodder at iso-nitrogenous and iso-energetic conditions. According to [14], this has involved the application of a substitution ratio of about 0.68 $kg_{soy\text{-}meal}/kg_{DDGS}$ (defined assuming a DDGS protein content of about 76% compared to soy-meal). Then, the DDGS protein content (and, hence, the substitution ratio response to nitrogen) has been scaled according to the nitrogen dosage applied.

On the other hand, both economic and environmental parameters has been defined adapting the approaches of [7,15] by varying the nitrogen-dependent inputs according to the trend in the response curves.

3. Results and discussion

The modelling framework as presented was used to determine the optimal system configuration according to the two conflicting objectives discussed in the above. Design variables (the nitrogen dosage over the biomass crop field and the DDGS end-use option) were optimised by means of the CPLEX solver in the GAMS® modelling tool [16]. The model considers two technological options for DDGS end-use: *i)* soy-meal substitute to be sold in the animal fodder market, or *ii)* fuel fed to a combined heat and power (CHP) station.
A first instance has been assessed by assuming standard market conditions for the electricity selling price ($MPd_{n,2}$ = 91.34 €/MWh_e). The sub-optimal set of solutions (◆) coming from the trade-off between the environmental (total impact, TI, expressed in kt CO_2-eq) and the financial (Net Present Value, NPV, expressed in M€) criteria is reported in Fig. 1.

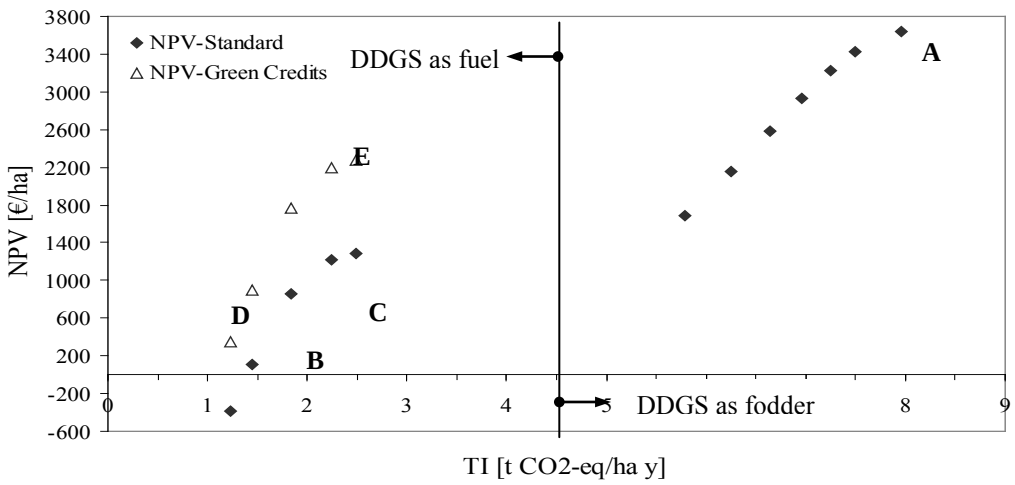


Fig. 1. Pareto set of solutions: NPV vs. Total Impact (TI)

Point A on the diagram represents the best optimum in terms of economic performance that can be obtained by applying a nitrogen dosage of 237.5 kg_N/ha and using DDGS as animal fodder substitute. However, this is not a feasible solution if we consider the EU targets (which impose a minimum of 50% of emission savings with respect to conventional fuels by 2017): point A, indeed, corresponds to a GHG emissions reduction of about 21% that totally amount to 238.9 kt CO_2-eq (about 67.6 kg CO_2-eq/GJ_{EtOH}). The mentioned target is never met if we

keep using the DDGS as animal feed substitute. Thus, it is worth to investigate on the other alternative, namely the use of DDGS to fuel a CHP station. In this case, we assist to a sensible GHG emissions reduction by still remaining within the economic feasibility region. It is possible to obtain payback times lower than 6 years from point B up to point C. The environmental optima (that also assures feasible economic conditions) involves a nitrogen dosage of 87.5 kg_N/ha (point B) so allowing for a GHG emissions reduction of about 80% (17.1 kg CO_2-eq/GJ_{EtOH}) with respect to gasoline and realising an NPV of about 25.7 M€ (the payback time is still reasonable and amounting to about 6 years). On the other hand, the financial optima (still assuring feasible environmental performance) involves a g reater nitrogen dosage (162.5 kg_N/ha, point C) so resulting in higher GHG emissions, although still more than acceptable (21.2 kg CO_2-eq/GJ_{EtOH}, corresponding to 75% of emissions savings with respect to gasoline), and realises an NPV of about 38.5 M€ (the payback time is now 5.5 years).

The situation might be even more profitable if the bioethanol business would be supported by governmental subsidies, as it is actually envisaged according to the latest Italian regulation on renewable energy: accordingly the electric energy produced from renewable energy sources can be sold at a price of 180 €/MWh_e. The positive effect of these subsidies is evident from the set of sub-optimal solutions (△) reported in Fig. 1. Considering the solution involving DDGS as animal feed substitute, the situation does not change because green credits do not affect the financial features of this option. On the other hand, the financial performance is actually enhanced if DDGS is used to fuel a CHP station: the points between D and E represent feasible options in terms of both economic and environmental criteria. For instance, by applying a nitrogen dosage of 37.5 kg_N/ha (point D) the environmental optima entails a GHG emissions reduction amounting to about 82% (15.8 kg CO2-eq/GJ_{EtOH}) with an economic profit of about 27 M€ over a 10 years horizon (the payback time is about 6 years, still). However, if the profit maximisation is preferred, it is possible to apply up to 162.5 kg_N/ha (point E) so as to keep within the environmental feasibility region (the GHG emissions reduction would be 75% with respect to gasoline) and realising excellent financial performance: as shown in Figure 7.6, the NPV now amounts to 68.4 M€ so allowing for the lowest payback time (4 years).

4. Conclusions

It is clear that the analysis of biofuels production is a complex task, particularly when environmental issues are taken into account. Broader information, analysis tools, interactions between different types of expertise are necessary to obtain a full comprehension of such a multifaceted problem. If the final goal is fuel instead of food, the overall chain might have to be operated in a different way and the boundary between “first-generation” and “second-generation” biofuels may start blurring. This is why decision makers should be provided with tools capable of evaluating how the system may react to different options and how its design may change if optimised towards specific goals. On the one side, it is important to identify the existing optimal points; on the other hand, we need to assess how flexible the system is in terms of profitability, GHG emissions and environmental and social impacts.

In this contribution we showed how whole-system optimisation tools can be exploited to address these issues. We considered the nitrogen balance optimisation and the technology selection in a first generation bioethanol supply chain according to economic and environmental goals. Results demonstrate that the only way to meet the EU standards (50% of GHG emission savings by 2017) on corn bioethanol in Italy is to adopt a technological solution envisaging the construction of a CHP station to be fuelled with DDGS. This requires

moderate nitrogen dosage as a mineral fertiliser (about 160 kg_N/ha) so as to reach GHG emission savings of about 75% with respect to gasoline production. It is also worth mentioning that a more thoughtful use of mineral fertiliser would also reduce other environmental impacts associated with fixed nitrogen application to agricultural soils (i.e. eutrophication and acidification of the ecosystem). However, this would require support through the deployment of governmental subsidies so as to ensure all the competitiveness and economic efficiency requirements imposed by the global market.

Over the years, the discussion has broadened by incorporating the analysis of the entire supply chain and more recently even the indirect effects of land use change. In fact, future work will need to deal the analysis and modelling of the effects that the land conversion from crop-for-food to crop-for-fuel would generate.

References

[1] J. Fargione et al., Land clearing and the biofuel carbon debt, Science 319, 2008, pp. 1235–1238.

[2] T. Searchinger et al., Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change, Science 319, 2008, pp. 1238–1240.

[3] S. Kim and B. Dale, Life cycle assessment of fuel ethanol derived from corn grain via dry milling, Bioresource Technology 99, 2008, pp. 5250–5260.

[4] E.C. Petrou and C.P. Pappis, Biofuels: A survey on pros and cons, Energy & Fuels 23, 2009, pp.1055–1066.

[5] S.C. Davis et al., Life-cycle analysis and the ecology of biofuels, Trends in Plant Science 14, 2009, pp. 140–146.

[6] E. Gnansounou et al., Life cycle assessment of biofuels: Energy and greenhouse gas balances, Bioresource Technology 100, 2009, pp. 4919–4930.

[7] A. Zamboni et al., Spatially explicit static model for the strategic design of future bioethanol production systems. 2. Multiobjective environmental optimization, Energy & Fuels 23, 2009, pp. 5134–5143.

[8] G.P. Robertson et al., Sustainable biofuels redux, Science 322, 2008, pp. 49–50.

[9] N.V. Sahinidis et al., Optimization model for long range planning in the chemical industry, Computers & Chemical Engineering 13, 1989, pp. 1049–1063.

[10] P. Tsiakis et al., Design of multi-echelon supply chain networks under demand uncertainty, Industrial & Engineering Chemistry Research 40, 2001, pp. 3585−3604.

[11] S.M Peters et al., Plant design and economics for chemical engineers, McGraw-Hill, 2003.

[12] Agra Informa website: www.agra-net.com.

[13] T.C Smith et al., Wheat as a Feedstock for Alcohol Production, HGCA, 2006.

[14] U. Meyer et al., Effects of by-products from biofuel production on the performance of growing fattening bulls, Animal Feed Science and Technology 161, 2010, pp. 132–139.

[15] G. Franceschin et al., Ethanol from corn: A technical and economical assessment based on different scenarios, Chemical Engineering Research & Design 86, 2008, pp. 488–498.

[16] R.E. Rosenthal, GAMS - A Users' Guide (Version 22.5). GAMS Development Corporation, 2006.

Effects of Biodiesel Fuel Use on Vehicle Emissions

Larry G. Anderson[1,*]

[1] *University of Colorado Denver, Denver, Colorado, USA*
** Corresponding author. Tel: +1 3035562963, Fax: +1 3035564776, E-mail: larry.anderson@ucdenver.edu*

Abstract: Many countries are using and considering the increased use of biodiesel blended fuels to slow their growth of fossil fuel use for transportation purposes. Before the use of biodiesel fuels increase, it is critical that we understand the effect of using biodiesel blends on vehicle emissions, so that we better understand what air quality impacts to expect. Many previous reviews of biodiesel effects on emissions have combined all of the emissions data available to construct a single value for the effects on pollutant emissions. This includes combining emissions data from both light-duty and heavy-duty diesel vehicles and engines, combining vehicle data from chassis dynamometer and on-road emissions testing. In this review, we will analyze the effects on vehicle emissions of switching from petroleum diesel fuel to biodiesel blended fuels for light-duty and heavy-duty vehicles, separately. We will not include engine emissions data in this analysis. For the heavy-duty vehicles, we will also separate results for on-road emissions testing from chassis dynamometer testing. The emissions of regulated pollutants will be evaluated, including hydrocarbons (HC), nitrogen oxides (NOx), carbon monoxide (CO) and particulate matter (PM), as well as carbon dioxide (CO_2) emissions and fuel economy. In these analyses, we have found some statistically significant differences in the effects of biodiesel use on the emissions between heavy-duty vehicles based on dynamometer and on-road emissions testing, and light-duty vehicle dynamometer data. For vehicle emissions from heavy-duty vehicle tested using a dynamometer and on-road emissions techniques, the emissions of CO, CO_2 and PM were found not to be significantly different for B20, but the HC, NOx and fuel economy results were significantly different. The results of the heavy-duty and light-duty dynamometer emissions were found to not differ significantly for any pollutant, other than PM emissions when B20 blended fuels were used. When the results of the emissions studies were not significantly different, the results were combined to determine the effect of biodiesel use on vehicle emissions.

Keywords: *Renewable fuels, Biodiesel, Vehicle emissions, Regulated air pollutants, Hazardous air pollutants*

1. Introduction

Many countries are evaluating a variety of alternative fuels for use in motor vehicles in an attempt to reduce greenhouse gas emissions and to improve the energy security of the country. Biodiesel and other biofuels are substitute fuels capable of replacing fossil fuels on a large scale in the transportation sector. Although biodiesel currently accounts for a small portion of the total diesel fuel used, increasing its use requires that we understand the impact that biodiesel could have on vehicle emissions, and ultimately on air quality.

Vehicle emissions are affected by the fuel that is used. There have been several reviews of the effects of biodiesel fuel use on emissions, but many of these have used engine emissions tests in addition to or instead of vehicle emissions tests [1-4]. Emission measurement methods include engine and chassis dynamometer tests, tunnel studies, and more recently, remote sensing and portable (or on-board) emissions monitoring systems. Engine dynamometer systems are quite useful for research purposes, but because these systems test only the engine, they are missing many factors that may affect the real-world emissions of vehicles. Chassis dynamometer studies test the entire vehicle and can use realistic driving cycles which are expected to produce more representative emissions results. Chassis dynamometer testing is more complicated and expensive than engine testing, so less of that data is available. Remote sensing and on-board emissions measurements have also been used to assess the effects of using different fuels on vehicle emissions. Remote sensing uses spectroscopic measurements of a vehicle that passes through the light beam to measure the concentrations of emitted pollutants. These measurements provide only a snapshot of the emissions at a particular

location and thus cannot characterize an entire operating cycle for a vehicle. On-board emissions measurement systems offer the advantage of being able to capture real-world emissions during an entire operating cycle for the vehicle. In this review, we will focus on the analysis of vehicle emissions data that is more representative of real-world operating conditions, from chassis dynamometer and on-board emissions measurement systems.

2. Analysis Approach

In this paper, we will assess the impact of biodiesel fuel use by looking at the relative value of a property, such as pollutant emissions from a biodiesel blended fuel divided by that from conventional diesel fuel use for a particular vehicle. This reduces some of the variability in analyzing vehicle emissions data, since vehicles that emit larger or smaller quantities of a pollutant when using diesel fuel are expected to also emit larger or smaller quantities of that pollutant when using a biodiesel blended fuel. If the use of biodiesel fuels does not affect the property being studied the relative value will be 1. For example, a value of 1.12 indicates that the property has increased by 12% with biodiesel fuel use and a value of 0.89 would indicate a decrease by 11% with biodiesel fuel use. In this analysis, at least twenty measurements were required to assess statistical significance. This minimum number of measurements was used in an attempt to assure the representativeness of the data. These relative emissions and fuel economy data were tested for normality using the Lilliefors test. These data were found not to be significantly different from a normal distribution. This allows the use of conventional statistical techniques in these analyses.

3. Heavy-Duty Diesel Vehicle Emissions

Quite a bit of data exists for biodiesel blended fuels in heavy-duty (HD) diesel vehicles where the emissions were measured using chassis dynamometers and on-road using portable emissions monitoring systems (PEMS). These two different sources of emissions data will be analyzed separately.

3.1. Heavy-Duty Diesel Chassis Dynamometer Studies

The data used to assess the effect of biodiesel fuels use on HD vehicles from dynamometer studies comes from 19 different studies and includes 124 different tests. Much of the data on the emissions effects of biodiesel blended fuels from chassis dynamometer studies of HD diesel vehicles was for 20% blends of biodiesel with petroleum diesel (B20) and neat biodiesel (B100) fuels. Since a total of twenty valid measurements are required in order to assess the significance of the effect of biodiesel blended fuels on a measurement, only hydrocarbons (HC), nitrogen oxides (NOx) and carbon monoxide (CO) had sufficient data for the assessment of both B20 and B100 biodiesel, while sufficient data was also available for B20 blends to assess the significance of the effects on carbon dioxide (CO_2), particulate matter (PM) and fuel economy. For these HD vehicles, the use of biodiesel led to a decrease for hydrocarbon emissions of 5.7 ± 4.4% (95% confidence interval) for B20 and 23.0 ± 9.2% for B100, a decrease for CO emissions of 4.1 ± 6.4% (not significant) for B20 and 24.0 ± 7.2% for B100, and an increase in NOx emissions of 3.5 ± 2.3% for B20 and 9.0 ± 2.8% for B100. The use of B20 blended fuels also led to a decrease for CO_2 emissions of 0.4 ± 1.0% (not significant), for PM emissions of 13.3 ± 5.1%, and for fuel economy of 2.6 ± 1.2%. There was an insufficient quantity of emissions test data for other biodiesel blends to characterize the variability in the emissions data, and to allow one to reliably assess the significance of the effects on the emissions of HD vehicles tested using chassis dynamometers.

3.2. Heavy-Duty Diesel On-Road Vehicle Emissions Studies

The data used to assess the effect of biodiesel fuels use on HD vehicles from on-road studies comes from 14 different studies and includes 94 different tests. Almost all of the data for these on-road vehicle emissions tests of HD diesel vehicles are for B20 blends. For these HD vehicles, the use of B20 blends led to a decrease for hydrocarbon emissions of 21.7 ± 4.4% (95% confidence interval), a decrease for CO emissions of 6.6 ± 5.4%, and a decrease in NOx emissions of 3.3 ± 3.4% (not significant). The use of B20 blended fuels also led to an increase for CO_2 emissions of 3.0 ± 3.6% (not significant), a decrease for PM emissions of 15.2 ± 6.0%, and an increase for fuel economy of 6.3 ± 8.1% (not significant). One of the major complications of the on-road PEMS testing for evaluating different fuels is the much poorer matching of the operating conditions of the vehicles with these different fuels. This generally leads to increased variability in the results.

3.3. Differences between Chassis Dynamometer and On-Road Heavy-Duty Vehicle Emissions Data

The chassis dynamometer and on-road vehicle emissions data for HD vehicles were tested to determine if the results were significantly different for these two testing procedures. It was found that there was no significant difference in the results of the emissions test methods for the CO, CO_2 and PM data using B20 blends. However, the results were significantly different for the HC, NOx and fuel economy data between the two data sets. For the HC data, B20 blends led to a significant decrease in HC emissions in both cases, but only about 5.7% for the dynamometer studies and 21.7% for the on-road studies. The decrease from the on-road studies with B20 were similar to the effects of B100 seen with the dynamometer data. For the NOx data, B20 blends led to a significant increase in NOx emissions of about 3.5% for the dynamometer studies, while there was a 3.3% decrease (not significant) in NOx emissions in the on-road studies. The data continues to support an increase in NOx emissions with biodiesel blends in HD diesel vehicles. In the case of the fuel economy data, B20 blends led to significantly lower fuel economy of about 2.6% from the dynamometer studies, but led to a 5.7% increase (not significant) in fuel economy for the on-road studies. The data continues to support a decrease in fuel economy with B20 biodiesel blends in HD vehicles.

Since there was no significant difference in the results of the dynamometer and on-road emissions studies using B20 blends for the HD vehicle emissions of CO, CO_2 and PM, these data sets were combined and the significance of the effects on this larger pooled data set were assessed. For the CO emissions data with B20, a 4.1% decrease (not significant) was found from the dynamometer studies and a significant 6.6% decrease was found from the on-road studies. With the combined data set, a significant decrease of 5.3 ± 4.1% was found for CO using B20 blends. For the CO_2 emissions data with B20, a 0.4% decrease (not significant) was found from the dynamometer studies and a 3.0% increase (not significant) was found from the on-road studies. With the combined data set, a 1.6 ± 2.2% increase (not significant) was found for CO_2 using B20 blends. These data support the conclusion that the use of B20 biodiesel fuels has no significant effects on the emissions of CO_2. For the PM emissions data with B20, a significant 13.8% decrease was found from the dynamometer studies and a significant 15.2% decrease was found from the on-road studies. With the combined data set, a significant decrease of 14.5 ± 3.9% was found for PM using B20 blends.

4. Light-Duty Diesel Vehicle Emissions using Chassis Dynamometers

The data used to assess the effect of biodiesel fuels use on light-duty (LD) vehicles from dynamometer studies comes from 47 different studies and includes 259 different tests. LD

diesel vehicle emissions have been measured almost exclusively by use of chassis dynamometers. PEMS have not been used extensively in the study of LD diesel vehicle emissions. The available data consists of a number of studies conducted in North America, Europe, Asia and Australia. The studies conducted in North America tend to be dominated by studies of larger vehicles, including pickup trucks, while those elsewhere in the world include a larger fraction of cars, passenger and delivery vans. This data set also includes biodiesel fuels that are made from different biooil feedstock (soy, rapeseed, canola, palm, coconut, used cooking oils, animal fats, etc.). The emissions test data for light-duty vehicles contains many more tests with varying biodiesel percentages, not largely B20 and B100.

Fig. 1 shows the relative emissions of HC, NO_x, CO, CO_2, PM and fuel economy effects of using various biodiesel blended fuels based on chassis dynamometer testing of LD vehicles from a number of different studies. From this figure it is clear that there is a relatively large quantity of data available with different biodiesel percentages, and that there is considerable variability in the individual measurements of the relative emissions effects of biodiesel blended fuels. Similar figures are seen when one looks at the HD diesel emissions data. For the regulated pollutant emissions, there are more that 20 sets of test results available for the B5, B10, B20, B30, B50 and B100 biodiesel blends. This allows the evaluation of statistical significance of the effects of these blends on vehicle emissions.

For the LD diesel vehicle emissions we observed the following effects of the biodiesel blended fuels. For the HC emissions the effects of the biodiesel blends is an increase of 1.6 ± 4.5% (95% confidence interval) for B5, an increase of 4.2 ± 5.2% for B10, a decrease of 4.1 ± 5.5% for B20, a decrease of 0.3 ± 5.4% for B30, a decrease of 0.9 ± 10.3% for B50, and a decrease of 5.8 ± 14.8% for B100. None of the observed effects on hydrocarbon emissions are statistically significant. For NOx emissions the effects of the biodiesel blends was an increase of 1.1 ± 2.7% for B5, of 5.1 ± 2.3% for B10, of 5.8 ± 2.2% for B20, of 7.2 ± 2.7% for B30, of 7.3 ± 3.5% for B50, and of 6.5 ± 3.5% for B100. The biodiesel blend effect on NOx emissions is consistently a statistically significant increase for all of these blend levels, except B5. The effect of the biodiesel blends on CO emissions show a decrease of 0.7 ± 2.9% for B5, an increase of 2.7 ± 5.9% for B10, a decrease of 5.5 ± 3.5% for B20, an increase of 4.8 ± 6.0% for B30, an increase of 4.7 ± 10.8% for B50, and an increase of 12.9 ± 14.3% for B100. For the CO emissions, none of the biodiesel blends above had a statistically significant effect, except the decrease observed for the B20 blend. For the CO_2 emissions the effects of the biodiesel blends was a decrease of 2.0 ± 2.3% for B5, a decrease of 1.1 ± 0.9% for B10, a decrease of 0.4 ± 1.2% for B20, an increase of 1.1 ±1.4% for B30, an increase of 1.2 ± 1.3% for B50, and an increase of 0.8 ± 1.4% for B100. This data shows a small statistically significant decrease in CO_2 emissions only for the B10 blend. None of the other results are statistically significant. The effect of the biodiesel blends on PM emissions show a decrease of 1.0 ± 5.0% for B5, a decrease of 14.8 ± 3.5% for B10, a decrease of 5.8 ± 4.9% for B20, a decrease of 16.0 ± 3.6% for B30, a decrease of 9.1 ± 8.6% for B50, and a decrease of 7.0 ± 14.8% for B100. The decrease observed for the B10, B20, B30 and B50 blends are statistically significant, and they are relatively large effects in the range of 6-16% decrease, but none of the other biodiesel blend levels resulted in a statistically significant effect. For the fuel economy results, only the B5, B10, B20, B30 and B50 blends had a sufficient quantity of data (more than 20 values) to assess the significance of the effects. The fuel economy was found to decrease (or fuel consumption increased) by 0.4 ± 1.2% for B5, by 0.3 ± 1.0% for B10, by 1.0 ± 1.8% for B20, by 1.3 ± 2.0% for B30, and by 1.9 ± 2.5% for B50. None of the fuel economy effects are statistically significant.

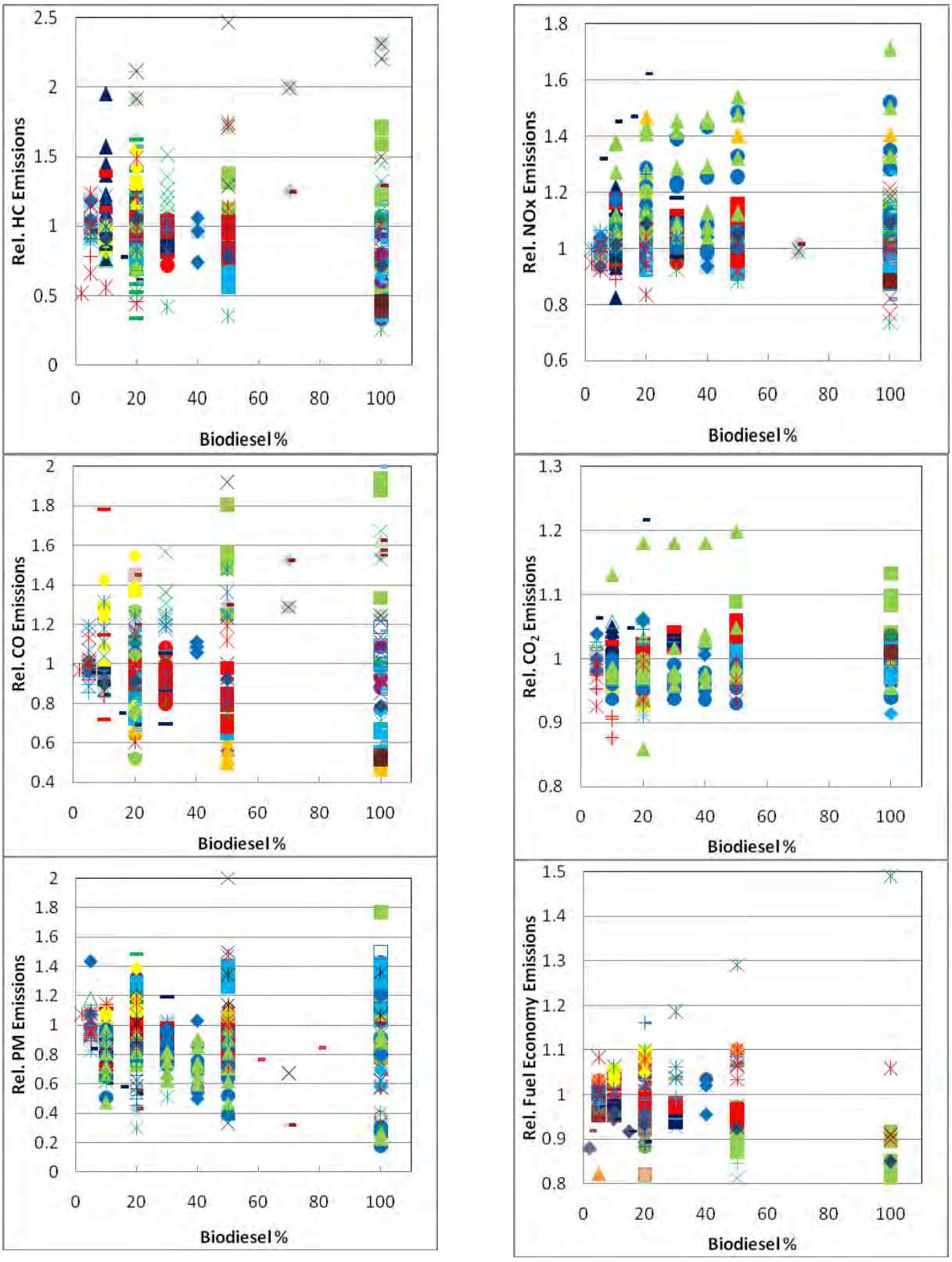


Fig. 1. Chassis dynamometer test results of relative emissions of hydrocarbons, nitrogen oxides, carbon monoxide, carbon dioxide, particulate matter, and vehicle fuel economy for biodiesel fuel relative to diesel fuel in light-duty diesel vehicles.

Sufficient data exists to allow one to begin to explore the effects of biodiesel fuel use on the emissions of formaldehyde, acetaldehyde and total polycyclic aromatic hydrocarbons (PAH) for LD vehicles. The effects of the biodiesel blends on formaldehyde emissions were increases of 28.9 ± 17.1% for B10, 27.5 ± 21.8% for B20 and 34.9 ± 8.7% for B30, while the effects on acetaldehyde emissions were increases of 40.7 ± 76.1% for B10, 69.9 ± 126% for B20 and 23.1 ± 7.2% for B30. All of the increases found for formaldehyde emissions were statistically significant, but only the acetaldehyde emissions increase for B30 was statistically significant. The results for the effects of the biodiesel blends on the emissions of total PAH were confusing, with the total PAH emissions reduced by 8.3 ± 6.4% for B10 and 8.9 ± 9.8% for B20, while for the B30 and B100 blends, the total PAH emissions increased by 21.2 ± 18.4% and 33.4 ± 53.7% respectively. Only the results for B10 and B30 were statistically significant.

5. Comparison of Heavy-Duty and Light-Duty Diesel Vehicle Emissions

The only comparisons that can be made between HD and LD diesel vehicle emissions are for B20 blends, where sufficient data exists for the HD diesel dynamometer and on-road and LD dynamometer tests, and for HC, NOx and CO emissions where sufficient data exists for HD and LD dynamometer tests with B100 fuels. For the HC emissions, we have found that the emissions from HD vehicles in the on-road emissions studies are significantly lower that the HD dynamometer test results. The HD on-road emissions results are also significantly lower than the LD dynamometer results, and the HD and LD dynamometer results are not significantly different from each other. The HD and LD dynamometer results have been combined for the B20 blend, resulting in an overall HC emissions decrease of 4.9 ± 3.5% from the combined dynamometer data. Again for NOx emissions, the HD on-road emissions results were significantly lower than the HD dynamometer results and were significantly lower than the LD dynamometer results. There was no significant difference between the HD and LD dynamometer results for NOx. The HD and LD dynamometer results have been combined for the B20 blend, resulting in an overall NOx emissions increase of 4.7 ± 1.6%. For the CO emissions, the HD on-road emissions results were not significantly different that the HD dynamometer results, and the combined HD emissions results were not significantly different than the LD dynamometer results. The HD dynamometer and on-road emissions results, and the LD dynamometer emissions results were combined for the B20 blend, resulting in an overall CO emissions decrease of 5.4 ± 2.9%. For the CO_2 emissions, the HD on-road emissions results were not significantly different that the HD dynamometer results, and the combined HD emissions results were not significantly different than the LD dynamometer results. The HD dynamometer and on-road emissions results and the LD dynamometer emissions results were combined for the B20 blend, resulting in an overall CO_2 emissions increase of 0.9 ± 1.5%. For the PM emissions, the HD on-road emissions results were not significantly different that the HD dynamometer results, but the combined HD emissions results were significantly lower than the LD dynamometer results. The HD dynamometer and on-road emissions results were combined for the B20 blend, resulting in an overall PM emissions decrease of 14.5 ± 3.9%. The fuel economy from HD vehicles in the on-road studies are significantly higher than the HD dynamometer test results. The HD on-road fuel economy results are not significantly different from the LD dynamometer results, and the HD and LD dynamometer results are not significantly different from each other. The HD and LD dynamometer results have been combined for the B20 blend, resulting in an overall fuel economy decrease of 1.8 ± 1.1%.

For the HC emissions from B100 blends, we have found that the emissions from HD and LD dynamometer data are not significantly different. The HD and LD dynamometer results have been combined for the B100 blend, resulting in an overall HC emissions decrease of 13.4 ±

9.2%. For the NOx emissions from B100 blends, the emissions from HD and LD dynamometer data are not significantly different. The HD and LD dynamometer results have been combined for the B100 blend, resulting in an overall NOx emissions increase of 7.5 ± 2.4%. For the CO emissions from the B100 blend, the heavy duty dynamometer results are significantly lower than the LD dynamometer results.

6. Conclusions

Most reviews of the effects of biodiesel blended fuels use on vehicle emissions combine all of the available data engine and vehicle, LD and HD to assess the effects. As has been found in this work this is not always a valid approach. In this work, we have only used vehicle emissions data, no engine data, and we have found some significant differences in subsets of this vehicle data.

In this work, it was found that there some of the emissions for HD diesel vehicles tested using dynamometers and on-road were significantly different. For B20 blends, the HC emissions for both test procedures led to significant decreases emissions in these emissions of 5.7% for the dynamometer studies and 21.7% for the on-road studies. In the cases of NOx emissions studies, a statistically significant increase in NOx emissions was found for B20 blends from the dynamometer data, while the on-road studies resulted in a 3.3% decrease that was not significant. For fuel economy, the dynamometer data for B20 showed a significant decrease in fuel economy of 2.6%, while the on-road data gave a 5.7% increase that was not significant. For each of these three measures for the two different sources of HD vehicle emissions data, the dynamometer data was significantly different from the on-road data. It is not be valid to combine data from the dynamometer and on-road studies of B20 blended fuels for HC and NOx emissions and fuel economy to determine the effects of using these fuels in HD vehicles. But since the B20 data for CO, CO_2 and PM emissions derived from these two different test procedures are not significantly different, it is valid to combine these data sets to assess the overall effects of B20 on these emissions from HD vehicles.

In comparing the results of studies on LD and HD vehicles for B20 blends, we have found no significant differences in HC and NOx emissions and fuel economy between the LD and HD dynamometer studies, and we have found no significant differences in emissions of CO and CO_2 between the LD dynamometer and the combined HD dynamometer and on-road test data. But the PM emissions for B20 fuels are significantly different between the LD dynamometer and the combined HD dynamometer and on-road test data. Table 1 summarizes the statistically significant results for B20 blended fuels, where the HD and LD data are combined when there is no significant difference between the subsets of the data.

Being able to partition data to allow one to explore subsets of vehicle emissions data requires large quantities of data. Many other factors need to be explored, but there is a shortage of adequate data to be representative of these other factors. There is inadequate data available to allow one to assess the effects of biodiesel fuel use on emissions of hazardous air pollutants, such as benzene, 1,3-butadiene, etc. As seen in this work, there is sufficient data to begin exploring the effects on LD vehicle emissions of formaldehyde, acetaldehyde, and polycyclic aromatic hydrocarbons. We need much more data to begin assessing the effects of biodiesel fuel use on ultrafine particulate emissions, especially, particle number and particle size distributions in emissions. Different biodiesel feedstocks are more commonly used in different areas of the world, such as soy oil in North America, rapeseed oil in Europe and palm oil in southern parts of Asia. Additional vehicle emissions data is necessary to explore the effects of different biodiesel feedstocks on vehicle emissions.

Table 1. Summary of statistically significant results for B20 and B100 biodiesel blends for combined LD and HD dynamometer (dyno) and HD on-road emissions data.

Emission	Biodiesel Blend	Tests	Biodiesel Effect	95% Confidence Interval	Number of Measurements
HC	B20	HD & LD Dyno	-4.9%	±3.5%	204
HC	B20	HD On-road	-21.7%	±4.4%	89
HC	B100	HD & LD Dyno	-13.4%	±9.2%	122
NO_x	B20	HD & LD Dyno	+4.7%	±1.6%	227
NO_x	B100	HD & LD Dyno	+7.5%	±2.4%	143
CO	B20	HD, LD Dyno & HD On-road	-5.4%	±2.9%	286
PM	B20	HD Dyno & HD On-road	-14.5%	±13.9%	137
PM	B20	LD Dyno	-5.8%	±4.9%	109
Fuel Economy	B20	HD & LD Dyno	-1.8%	±1.1%	94

References

The literature that was reviewed in this analysis included 19 published studies using dynamometers for HD vehicles, 14 studies using on-road data for HD vehicles, and 47 studies using dynamometers for LD vehicles. Due to space limitations these references are not included in the reference list, but are available upon request.

[1] R. L. McCormick, The impact of biodiesel on pollutant emissions and public health, Inhalation Toxicology 19, 2007, pp. 1033 – 1039.

[2] M. Lapuerta, O. Armas, J. Rodriguez-Fernandez, Effects of biodiesel fuels on diesel engine emissions, Progress in Energy and Combustion Science 34, 2008, pp. 198- 224.

[3] J. Yanowitz, R. L. McCormick, Effect of biodiesel blends on North American heavy-duty diesel engine emissions, European Journal of Lipid Science and Technology 111, 2009, pp. 763-772.

[4] S. K. Hoekman, A. Gertler, A. Broch, C. Robbins, Investigation of biodistillates as potential blendstocks for transportation fuels, Coordinating Research Council, CRC Project No. AVFL-17, 2009.

First experiences of ethanol hybrid buses operating in public transport

Martina Wikström[1,*], Anders Folkesson[2], Per Alvfors[1]

[1] *Chemical Engineering and Technology, Division of Energy Processes, Royal Institute of Technology, Stockholm, Sweden*
[2] *Sustainable Solutions, Buses and Coaches, Scania CV AB, Södertälje, Sweden*
** Corresponding author. Tel: +46 8 790 65 51, Fax: +46 8 732 08 58, E-mail: marbjor@kth.se*

Abstract: With the ambitions to further increase its share of more sustainable vehicles, Stockholm Public Transport Authority (SL) carried out a project to evaluate the performance of ethanol hybrid buses together with bus manufacturer Scania and bus operator Nobina. Ethanol hybrid buses were operating in regular suburban public transport traffic in Stockholm between May 2009 and June 2010. The purpose of this paper is to evaluate the potential of the ethanol hybrid buses in general and their energy efficiency in particular. The evaluation is based on experimental data, mainly from standardised duty cycle tests, but also general experiences during the trail, for example error reports. The buses have a series hybrid powertrain with super capacitors as energy storage. At favourable conditions the fuel reduction is approximately 20 %. The potential additional fuel savings of the start/stop software has been tested and adds at least another 10 % fuel reduction. Not all of the hybrid system's components are yet robust enough, thus they need further development to fully commercial. Hybrid city buses have great potential but are currently not technically mature and proven, nor have the overall costs over the lifetime of the vehicle reached a commercial level as yet.

Keywords: *Ethanol hybrid bus, Series hybrid, Duty cycle, Urban public transportation, Energy analysis*

1. Introduction

Six ethanol hybrid buses and one reference bus were operated during a one-year field test to evaluate the robustness and energy saving potential of their hybrid powertrain. Partners in the project were the Stockholm Public Transport Authority (SL), the bus manufacturer Scania and the bus operator Nobina and it was carried out with funding from the Swedish Energy Agency. This is a unique project because it is one of the first times renewable-fuelled hybrid buses have been tested and operated in real traffic. The buses were operating in Stockholm's south suburban areas but were also taken out of traffic to perform standardised duty cycle tests on a test circuit, tests intended to better reflect inner-city driving. The objective of the field test from Scania's perspective was to test the hybrid powertrain in real traffic early in the development process in order to find weaknesses in the hybrid system. From SL's and Nobina's point of view the project aimed to evaluate the status and the potential of hybrid buses and was a way to enhance the development of even more environmentally friendly vehicles in their fleets. Already today (2010), SL has the world largest fleet of renewable-fuelled buses with more than 400 ethanol buses and 100 biogas buses in operation out of a fleet of around 2000 buses. The target is that 50 % of all buses should run on renewable fuels at the end of 2011 and 100 % by 2025 [1]. In this paper the general operational findings are presented with focus on evaluation of robustness of the powertrain (one-year field test) and the energy efficiency potential (duty cycle tests).

2. Methodology

The objectives are to evaluate the robustness and the energy efficiency potential of ethanol hybrid buses. In order to evaluate the robustness of the hybrid powertrain, the drivers and technicians filed error reports during the one-year field test. To attain reproducible experimental data in order to evaluate the energy efficiency potential, duty cycle tests were carried out. More details about the experimental set-up, see section *5. Experiments and results.*

3. Towards sustainable urban transportation

There are many reasons for promoting more sustainable urban transportation:

- To reduce emissions harmful to public health such as NOx, particulates and noise.
- To reduce emissions of greenhouse gases, most important fossil CO_2.
- To secure energy supply for the transport sector in the long term.

Additionally, by increasing the share of public transportation the problems with traffic congestion decrease. Traffic congestion becomes worse as the population in urban areas increases and cities become more densely populated while simultaneously more transports of people and goods must be carried out in the same or even less space than before.

The CO_2 emissions are, apart from increasing the share of public transport, tackled cost-efficient by shifting from fossil to renewable fuels. This has positive impact also on the energy security issue, especially if bio fuels may be produced locally. Bio fuels may sometimes be used as low-blends in fossil fuels, and sometimes as high-blends or pure fuels. There are political targets and also legislation for introduction of bio fuels in various regions, e.g. the EU is to have 10 % renewable fuels by 2020 [2]. A local example is the Swedish Government's vision that the Swedish transport sector should be independent of fossil fuels by 2030 [3]. Most widely spread renewable fuels are ethanol and biodiesel but other fuels, such as biogas are also getting increased attention in some markets [4].

At the same time as more bio fuels are introduced in the transport sector, vehicles must be as energy or fuel efficient as possible, irrespective of the fuels used, i.e. fossil and/or renewable. Striving for fuel efficiency is an ongoing process and has been the single most important force of competition in the commercial vehicle industry for decades – fuel efficiency improvements are introduced when commercially feasible. Commercially feasible refers to the lifecycle cost of an improvement in comparison with its expected benefits. This is for fuel efficiency improvements the development and production costs, expected lifetime, replacement cost if the lifetime of a new component is short as well as additional repair and maintenance costs measured against fuel cost saving or CO_2 saving. Hybridisation is one proposed method for vehicle fuel savings. A hybrid powertrain also gives the potential to improve the vehicle by other means and to make it more attractive for the passengers, e.g. noise impact can be minimised during start and acceleration since the internal combustion engine is assisted by one or more electric motors. If the vehicle has a series hybrid powertrain, i.e. a completely electric propulsion system, the powertrain usually offers a completely step less, and thereby very comfortable, drive without any jerks at all due to gear shifts. In this powertrain, there are also possibilities to improve the vehicle design and layout because there are basically no restrictions imposed by a mechanical transmission, prop shafts, cardan angles etc [5]. Even though hybrid buses seem to have a good potential there is no production of hybrid buses in common commercial terms, only small series production as tests and demo fleets, or politically driven and heavily subsidised fleets. In North America there are a few thousands hybrid buses running in Seattle, New York City, San Francisco and Toronto among other cities, all heavily subsidised by the government or local municipalities. The extra cost for hybridisation is usually very high, in the range of 100,000 € or even more extra per vehicle [6] and the technology is not yet proven, especially the energy storage systems (e.g. battery). Even so, hybrid buses, if designed and implemented in a clever and cost-efficient way, may play an important role in a future sustainable transport system due to their potential for energy saving, especially if combined with renewable fuels.

4. The bus

The ethanol hybrid bus is a Scania OmniLink, a three axis, 13.7 meter long low-entry city/suburban bus with a rear boggie. The internal combustion engine (ICE) is a diesel engine slightly adapted (e.g. higher compression ratio) to combust ethanol according to the diesel combustion process. The renewable fuel (ED95) used for the engine consists of 95 % ethanol and 5 % additives (ignition improver, lubricating additive etc). This is the third generation of ethanol engines from Scania since start of production in the late 1980s. So far around 700 ethanol buses have been delivered, mainly to Stockholm but also to number of cities worldwide.

The hybrid buses are equipped with a series hybrid powertrain, i.e. with fully electric propulsion. A 150 kW electric motor propels the mid axle of the bus. A high power and high torque generator is mounted on the internal combustion engine. The electric motor, generator and power electronics are delivered by Voith. The energy storage system in the hybrid powertrain consists of super capacitors, not batteries. Four 125 V modules from Maxwell connected in series offer total usable storage capacity of 400 Wh.

Fig 1. The Scania OmniLink ethanol hybrid bus and a schematic illustration of the series hybrid powertrain [Photo: Stefan Wallin, SL]

A reference bus with an identical ethanol engine but equipped with a conventional six-speed hydraulic automatic gearbox with retarder from ZF was also operated during the field test. The reference bus has the same identical exterior dimensions (excluding the roof hood containing the energy storage) and interior design as the hybrid bus. The only difference is that the hybrid buses have one seat missing in front of the rear door of the bus due to a conduit for cabling and coolant pipes to the power electronics and the energy storage system mounted on the roof. The hybrid bus is approximately 1.5 tonnes heavier than the reference bus.

Type: Scania OmniLink Low-entry city bus	Description
General	
Dimensions *(L × W × H)*	13.7 m × 2.55 m × 3.54 m
Kerb weight	16 tonnes
Max weight	26 tonnes
Passenger capacity	115 (40 + 75) (minus one seat in hybrids)
Internal Combustion Engine	Diesel ethanol engine
Fuel	ED95
Maximum Power output	198 kW (270 hp)
Maximum Torque	1 250 Nm
Emission level	Euro V / EEV
Hybrid components	
Type	Series hybrid
Electric motor	Voith TFM
Maximum Power	150 kW
Maximum Torque	2 750 Nm
Generator	Voith TFM
Maximum Power	220 kW
Maximum Torque	1 250 Nm
Energy Storage Unit	Maxwell Super Capacitors
Number of modules	4
Total capacity (useable)	400 Wh
Maximum voltage per unit	125 V
Maximum voltage in total	500 V

Fig 2. Technical description of the ethanol hybrid bus

5. Experiments and results

The one-year field test generated considerable experience as regards the robustness of the hybrid powertrain. In order to evaluate the energy efficiency potential, duty cycle tests were carried out to obtain experimental data representing various traffic situations. The nature of the suburban route did not produce data relevant for an energy flow analysis for city traffic.

5.1. Evaluation of powertrain robustness from one-year field test

Based on error reports filed by the drivers and technicians during the field test, the main malfunctions were divided into three categories: 1) ICE, internal combustion engine 2) the bus in general and 3) hybrid powertrain-related errors. To further evaluate the hybrid powertrain, this section is divided into four subgroups (a – d) to evaluate the robustness of its main areas. Compilation of results from error report is shown in Figure 3.

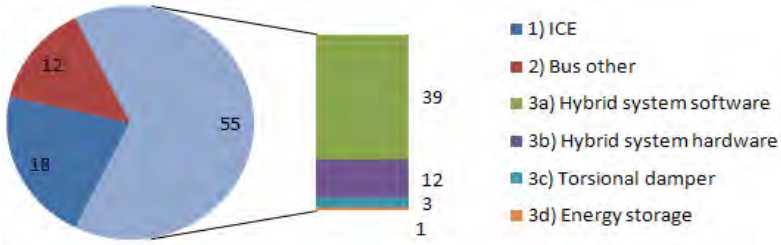


Fig 3. Error reports filed during the one-year field-test.

The robustness of the hybrid powertrain is the focus for this paper, but just to mention something about the other two categories, also the internal combustion engine underwent development during the field test period, e.g. the fuel injections system was improved. Upgrading the engine eliminated many of the errors reported during the first part of the test period. The hybrid software is still under development; during the field test it was too sensitive to interference from e.g. abnormal parameter values sent from other hybrid components as well as the 24 V system voltage level. Through maintenance charging of the 24 V start battery; the number of software reports was reduced. Malfunctions due to hardware are caused predominantly by three components: the direction sensor on the electric motor, the electric motor itself and the torsional damper between ICE and generator. Due to the hybrid management road safety system, incorrect indication of torque to the direction sensor will immediately shut down the system. Some sensors were malfunctioning and therefore replaced and other reported errors were just false alarms. The construction of the electric motor in the tested version was not durable enough for this 3-axle hybrid bus application and had a life of about 15 000 – 20 000 km in several buses causing many filed error reports. This problem arose rather late in the project and was not yet resolved when the field test ended, but is defined and considered possible to tackle with further development. The torsional damper (3c) was initially too weak and when replaced by a stronger one the problem was solved. The only problem reported concerning the energy storage was a fan failure and therefore not caused by the super capacitors. The super capacitors may, as far as this one-year field test is concerned, be regarded as suitable energy storage for the application as regards robustness.

5.2. Evaluation of energy efficiency potential by standardised duty cycle test

In order to evaluate the potential of the hybrid powertrain, standardised duty cycle tests, according to SORT – Standardised on-road tests cycles (developed by the International Association of Public Transport, UITP), were carried out. The key parameters in a traffic situation are the average speed and the number of stops per kilometre, see Table 1. Variations due to topography are neglected to make the test repeatable, hence duty cycles are assumed to be completely flat.

Table 1. Characteristics of the three SORT duty cycles, from UITP 2004 [7]

	SORT 1	SORT 2	SORT 3
Average speed [km/h]	12.6	18.6	26.3
Stops per kilometre	5.8	3.3	2.1
Time idling [%]	39.7	33.4	20.1
Cycle type	Urban	Mixed	Suburban

Figure 4 shows the three performed duty cycles' continuous velocity profile coupled with the energy content in the super capacitors expressed as the state-of-charge (SOC) where 100 % is fully charged and the lowest level is restricted to 25 % (half nominal voltage) to decrease the risk of chemical side reactions and thereby increase capacitor service life. Experiments show that the super capacitors obtain a high round-trip efficiency, generally above 90 %. Super capacitors have high power density [8] and are therefore a suitable energy storage units for heavy vehicles equipped with regenerative braking. The kinetic energy accumulated during deceleration, is converted in the electric motor into electric power charging the super capacitors. If not stored in the super capacitors, it will be used to propel the ICE via the generator or, last of all, dumped in the resistor as heat to the cooling system, see Figure 1. SORT 1 tests show dynamic energy storage management without long time periods of completely charged or empty super capacitors. As seen in Figure 4 already during the SORT 2 test the energy storage will be restricted in terms of size (400 Wh), i.e. the energy storage system is fully charged. During SORT 3 tests, the charge oscillates between its extreme values. The capacity of the energy storage system is therefore a limiting factor for a bus in driving situations similar to SORT 2 and 3 but feasible for SORT 1, urban operation.

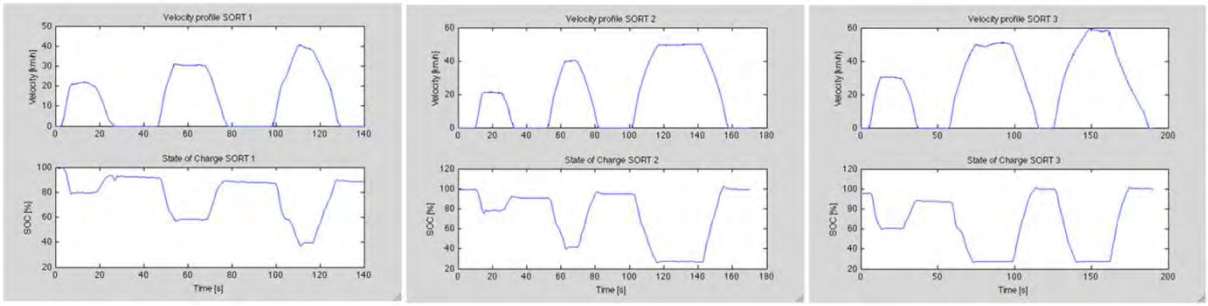


Fig 4. Velocity profile (top) and corresponding SOC profile (bottom) for SORT 1-3 test cycle

Performed SORT cycle tests with the reference bus enable quantification of the absolute fuel consumption reduction generated by the hybridisation, see Table 2.

Table 2. Fuel consumption SORT duty cycles.

	Reference Fuel consumption [litre/ 100 km]	Ethanol hybrid bus Fuel consumption [litre/ 100 km]
SORT 1	89.5	72.5
SORT 2	79.0	63.0
SORT 3	71.0	63.0

A significant fuel consumption reduction is attained for the cycles SORT 1 and SORT 2, 19 %, and 20 %, from 89.5 to 72.5 l/100 km and 79 to 63 l/100 km, respectively. The fuel consumption reduction for SORT 3 corresponds to 11 %, from 71 to 63 litre/100 km. In order to increase the level of detail, the energy spent per driving mode was explored, see Figure 5.

The four driving modes were defined as:

Idling – vehicle speed (υ) is zero, $\upsilon(i)=0$
Deceleration – when not idling and acceleration is negative $\upsilon(i) > \upsilon(i+1)$
Acceleration – when not idling and acceleration is positive $\upsilon(i) < \upsilon(i+1)$
Cruising – when not idling and acceleration is zero. $\upsilon(i) = \upsilon(i+1) \neq 0$

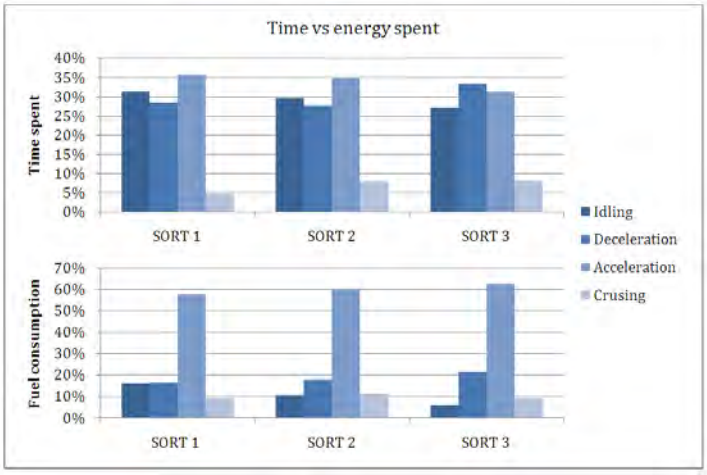


Fig 5. The energy and time spent per driving mode for duty cycle tests with hybrid bus according to the three SORT-cycles

Even though a large time is spent idling (about 1/3 of the time), the fuel consumption during this driving mode is moderate (between 5 and 15 %). The most fuel-consuming driving mode is acceleration where approximately 60 % (varies between 57.7 and 62.8 %) of the total fuel consumption is utilised during about 30-35 % of the time.

5.2.1. Start/stop

To further decrease the fuel consumption it is possible to install a software start/stop feature, which automatically turns of the ICE when idling. Analogous to the time spent as in Figure 5 the fuel consumption when the start/stop software operated was measured. The fuel consumption during idling drops drastically, now only consuming between 2.97 % (SORT 1) and less than 1 % (SORT 2 and 3). Decreasing the fuel demand during idling (which for the SORT cycles, corresponds to approximately 30 % of the time and in real traffic sometimes up to 60 % or more) has a significant impact on the overall fuel consumption, seen in Table 3:

Table 3. Fuel consumption during SORT duty cycles with the buses

	Reference [litre/ 100 km]	Ethanol hybrid bus [litre/ 100 km]	Ethanol hybrid bus with start/stop [litre/ 100 km]
SORT 1	89.5	-19 %	-33 %
SORT 2	79.0	-20 %	- 21 %
SORT 3	71.0	-11 %	- 13 %

5.2.2. Energy flow analysis using Sankey diagram

The energy flows through the electrified powertrain, see Figure 1, for the urban SORT cycle are illustrated in Figure 6 by a Sankey diagram. The Sankey diagram presents an average overview of the energy flows, and is not representative for a specific time during the cycle but is illustrative for the complete cycle. The energy flows in and out of key hybrid components are on-board measured data. The total power input is calculated from the instantaneous amount of fuel injected, in gram per stroke, using the lower heating value and density of ED95, 26.8 MJ/kg and 820 g/l, respectively. Losses for the ICE correspond to energy losses such as heat, mechanical and transmission losses. The energy consumption for running the auxiliary systems is also accounted for as an energy loss over the ICE. The efficiency in the generator is defined as the ratio between electrical power output and mechanical input. The generator and its inverter has experimentally proven to have an average efficiency of around 92 %.The energy storage efficiency, when SOC-balanced just as the round-trip efficiency, is calculated as the ratio between the total energy storage output and total energy storage input.

The energy storage efficiency is consistently about 90 % for all the three cycle tests. When decelerating, the electric motor operates as a generator and recovers brake energy. The share recovered brake energy almost exceeds 20 % of total power input. The efficiency of the electric motor is defined as the ratio between the average power input from the powertrain and the mechanical power output. The experimental average efficiency of the electric motor is approximate 92%. The share of power dumped upon the resistor during the SORT 1 cycle is small which indicates adequate energy storage size. The share, which is not regenerated, constitutes the term of losses due to aerodynamic drag, rolling resistance, transmission losses and wheel brakes.

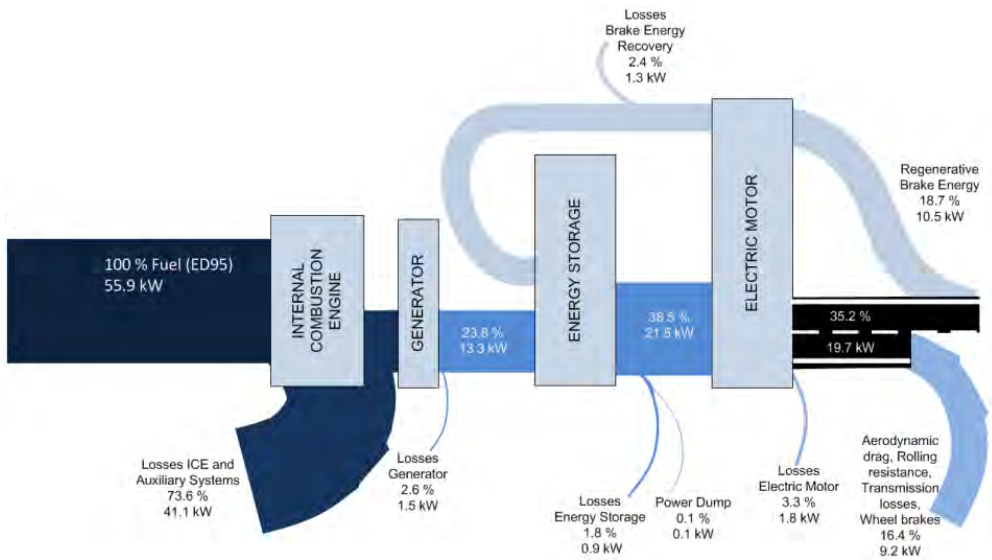


Fig 6. Sankey diagram of average, experimental power (energy) flows for the SORT 1 cycle

5.3. Field test – Urban Stockholm

The SORT 1 cycle tests indicated that the series hybrid system has high potential for significant fuel consumption savings. This lead up to a one-day field test in central Stockholm, during rush hour, to evaluate the potential of transferring the SORT results onto public transportation. Both the ethanol hybrid bus and the reference bus operated two routes: 2 and 66. To perform only a one-day test results in statistically uncertain values but still generates data that hopefully may indicate potential for urban regular transport. Due to organisational and legal reasons, since the bus operator participating in the project was not responsible for the inner-city bus routes, the city field test could not be prolonged.

Table 4. Characteristics of routes 2 and 66 in Stockholm

	Route 2	Route 66
Average velocity [km/h]	12.2	12.4
Stops per kilometre	6.15	5.0
Time idling [%]	25.4	22.36

The fuel consumption reductions are not of the same order as for the SORT tests. For route 66 the hybrid powertrain gives an insignificant (less than 1%) fuel consumption reduction. The fuel consumption may be reduced by 9.3 % for route 2. An explanation to the poor result might be related to the test method used, that the buses were operated nose-to-tail, a method that normally works well in a controlled environment such as a test track. However, in dense real traffic when, apart from consider the other bus, other vehicles and pedestrians as well as traffic regulations, the bus is subjected to weak accelerations and decelerations, which results in poor brake-recovery for the hybrid bus.

5.3.1. London Hybrid Bus Trials

The results from both the duty cycle tests and the field test are similar to the results of an extensive diesel hybrid bus trail in London, hosted by Transport for London (TfL), which also had difficulties in obtaining the significant fuel consumption reduction achieved during duty cycle test for regular public transport [6]. Based on the Millbrook proving ground's London Transport Bus (MLTB) test cycle the average fuel consumption reduction was 31 %, an average attained from series, parallel and mixed hybrid buses, both single and double-decked. During the hybrid bus trail in London, 56 hybrid buses operated 10 routes. The results were scattered between almost reaching the TfL 30 % reduction target and an actual increase in fuel consumption. For all vehicle manufactures, the results indicated a much smaller (or non-existing) fuel consumption reduction than expected. This indicates that fuel consumption reductions due to the hybridisation, when operating on public urban routes oscillate depending on the prevailing traffic situation since there are parameters in real-life traffic which can not be transferred to a test situation. A general conclusion from operation of hybrid buses in London is that the overall costs over the lifetime of a hybrid vehicle are not on a commercial level yet, i.e. the fuel savings do not equal the extra cost of the vehicles.

6. Experiences and conclusions

The series hybrid powertrain have experimentally shown potential for reducing the fuel consumption in urban traffic by up to 20 % and additionally 10 % when utilising the start/stop software. In conformity with similar experiments with hybrid buses, it is not evident that the fuel reduction potential may be realised on real life routes since the fuel reduction potential is dependent on the route characteristics. A recommendation for the next project is that the real inner-city fuel saving potential should be validated in real operation on inner-city bus routes. Some components of the hybrid system still need some development as regards robustness. The super capacitors did work consistently during the whole field test and may so far be considered to be suitable as energy storage for this hybrid vehicle application.

References

[1] Stockholm Public Transport (SL) web page, www.sl.se, accessed 2010-12-18

[2] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, Brussels

[3] The Swedish National Action Plan for the promotion of the use of renewable energy in accordance with Directive 2009/28/EC and the Commission Decision of 30.06.2009

[4] REN21, Renewables 2010, Global Status Report. Available at <www.ren21.net>, accessed 2010-12-14

[5] L. Overgaard, Scania hybrid concept – with robust technology into the future, Proceedings of 57th UITP World Congress, 2007

[6] Mike Weston, London Hybrid Bus Trials, Proceedings of Low Carbon Vehicle Partnership (LowCVP) Conference 2010, available at < www.lowcvp.org.uk >

[7] UITP, International Association of Public Transport, SORT – Standardised on-road test cycles, 2004. Available for purchase at < www.uitp.com >

[8] V. Paladini, T. Donateo, A. de Risi, D. Laforgia, Super-capacitors fuel-cell hybrid electric vehicle optimization and control strategy development, Energy Conversion and Management, Volume 48(11), 2007, Pages 3001-3008

Local production of bioethanol to meet the growing demands of a regional transport system

Lilia Daianova[1]*, Eva Thorin[1], Jinyue Yan[1, 2], Erik Dotzauer[1]

[1]*School of Sustainable Development of Society and Technology, Mälardalen University, Västerås, Sweden*
[2]*Royal Institute of Technology, Stockholm, Sweden*
** Corresponding author: Tel: +46 (0)21 10 15 38, Fax: +46 (0)21 10 14 80*
E-mail: lilia.daianova@mdh.se

Abstract: Energy security and the mitigation of greenhouse gas emissions (GHG) are the driving forces behind the development of renewable fuel sources worldwide. In Sweden, a relatively rapid development in bioethanol usage in transportation has been driven by the implementation of national taxation regulations on carbon neutral transport fuels. The demand for bioethanol to fuel transportation is growing and cannot be met through current domestic production alone. Lignocellulosic ethanol derived from agricultural crop residues may be a feasible alternative source of ethanol to secure a consistent regional fuel supply in Swedish climatic conditions. This paper analyzes how the regional energy system can contribute to reducing CO_2 emissions by realizing local small scale bioethanol production and substituting petrol fuel with high blend ethanol mixtures for private road transport. The results show that about 13 000 m^3 of bioethanol can be produced from the straw available in the studied region and that this amount can meet the current regional ethanol fuel demand. Replacing the current demand for petrol fuel for passenger cars with ethanol fuel can potentially reduce CO_2 emissions from transportation by 48%.

Keywords: *Agricultural crop residues, Straw, Bioethanol, Transport fuel, Greenhouse gas emissions (GHG)*

1. Introduction

According to the EU Directive, the target share of renewable energy sources as a percentage of gross final energy consumption in Sweden in 2020 is 49% [1]. Over the period 1990-2006 the proportion of renewable energy in final energy use has increased from 33.9% to 43.3%. Renewable electricity generation and renewable energy from the industrial sector contribute most to the proportion of renewable energy in final energy use in Sweden today with 18% and 14% respectively. Renewable energy use in the transport sector accounts for less than 1% of the final energy use [2].

Road traffic dominates in domestic Swedish transportation and contributes 93% of the total energy use in the transport sector (2009) [3]. Road transportation, which consists of private transport (mainly passenger cars), public transport and trucks, uses mostly fossil fuels, petrol and diesel. Use of renewable fuels such as ethanol, FAME (fatty acid methyl ester), biogas, and renewable electricity increased to 5.4% of the total energy use in transport by the end of 2009. Ethanol fuel made up 50% of liquid biofuels used in 2009 [3]. In 2007-2008 the corresponding share of ethanol fuel was almost 60% [4]. Along with a reduction in petrol fuel use in the last few years, ethanol use has also increased because almost all petrol is now a low blend E5 ethanol mixture. At the same time use of FAME and biogas increased by 8% and 1% respectively.

In Swedish transportation, the main current use of ethanol is as a 5% additive to petrol fuel (E5) or as high blend ethanol mixtures (E85, ED95). According to data presented by [3], from 2003-2009 the share of E5 in petrol fuel in Sweden increased from 45% to 95%. Total ethanol use in the Swedish transport sector increased from about 150 000 m^3 in 2003 to 391 000 m^3 in 2009 [5]. The use of low blend ethanol fuel (E5) grew from 125 000 m^3 to 229 000 m^3, whereas the use of high blend ethanol fuels (E85, ED95) grew from 25 000 m^3 to 162 000 m^3 during the period 2003-2009 [5].

However, domestic commercial ethanol fuel production in 2009 was 221 150 m^3. Currently, bioethanol is produced by Lantmännen Agroetanol in Norrköping by fermentation of wheat grains with a capacity of 210 000 m^3, which almost meets the demand for low blend ethanol. SEKAB in Örnsköldsvik produces 16 000 m^3 ethanol from sugary liquor from sulphite pulp from Domsjö Factories, and the SEKAB pilot plant [6] produces 150 m^3 ethanol from wood residues.

Ethanol demand in Sweden is much higher than domestic ethanol production. In the Swedish climate, cultivation of lignocellulosic biomass for bioethanol production is a possible alternative but there are still hurdles to overcome for the conversion of lignocelluloses to biomass. Consequently, realizing local small scale ethanol production can help regions to become more fossil fuel independent. This can also contribute to decreasing local environmental impact caused by transportation when replacing petrol fuel with renewable fuel. GHG emissions from road traffic totalled 29.1 million tonnes CO_2 eq in 2006, 63.6 % of the total Swedish transport sector emissions [7]. It is therefore of great importance to increase the use of biofuels in road transport, to make transport less dependent on fossil fuels and reduce GHG emissions.

GHG benefits of ethanol are discussed by Börjesson, where GHG emissions are estimated for the current Swedish grain-based ethanol production system [8]. Studies on technical performance of ethanol production integration with existing combined heat and power (CHP) plants have been published in recent years [9-11]. Models analysing road traffic energy demand and GHG emissions from transportation are developed for transport systems in China, Greece and Denmark [12, 13].

This paper focuses on analysing the potential for CO_2 emissions savings by substituting petrol use in the region with ethanol fuel, and does not consider the details of ethanol production. Based on an analysis of straw supply, current and potential ethanol and petrol fuel demand, we evaluate the possibilities for a self-sufficient road transport fuel system.

The present paper addresses the following questions. What is the regional demand for bioethanol, in 2009 and in 2020? Is there sufficient cereal straw available for local ethanol fuel production in the studied region in 2009 and 2020? What proportion of CO_2 emissions can be avoided in the region by substituting petrol use with ethanol fuel?

2. Methodology

In this study, input data is predominantly obtained from Swedish Official Statistics (SOS), which is also presented by state authorities (e.g. Swedish Energy Agency, Swedish Board of Agriculture) responsible for dissemination of statistical data in their respective areas. Input data collection is performed according to the structure shown in Figure 1.

The study region comprises the Sala-Heby municipalities, with around 35 000 inhabitants and a total area of 2 443 km^2 [5]. They are typical small municipalities with a predominantly service oriented economy. There are also small scale and decreasing farming and production industries and some tourist activities. A large part of the working population commutes to larger cities outside of the study region. Sala and Heby are neighbouring municipalities that belong to different counties (Västmanland and Uppsala) and are situated about 100 km northwest of Stockholm.

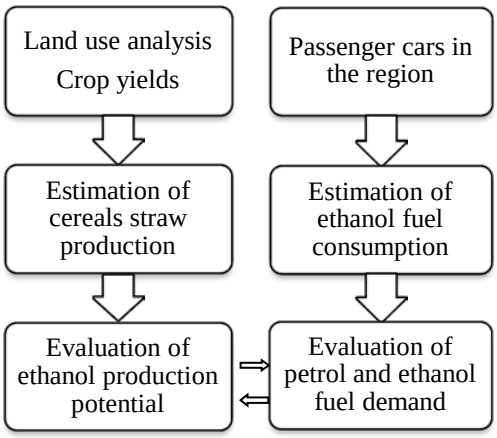


Fig. 1. A schematic flowchart for the local ethanol production study.

This paper focuses on analysing the potential for CO_2 emissions savings in the region by substituting petrol with ethanol fuel in transportation, ignoring the technological aspects of local small scale bioethanol production. The input year of the analysis is 2009. As cereal straw is considered as a feedstock for ethanol production in this study, all estimates are made for straw-based ethanol replacing regional petrol fuel demand. The study only considers fuel use by passenger cars as this is the dominant form of transport in regional road traffic.

In the Sala-Heby region, a total of 25 buses that run on diesel and biogas are used in public transportation. In Sala, the local public transportation company, Västmanlands Lokaltrafik, plans to substitute at least 10 of its 12 buses for biogas fuelled buses by 2014 [14]. In Heby, all 13 buses run on diesel and will be substituted with biogas buses during 2011-2012 according to the company's plan [15]. Buses are therefore excluded from the current analysis as none of the buses currently run on ethanol fuel and there are no plans for them to do so in future. Data on bus transportation in municipalities is obtained from local collective transportation companies as official statistical databases only present data on a regional level.

2.1. Data and assumptions

2.1.1. Straw supply and ethanol production potential

Input data is obtained from official statistics databases presented by the Swedish Board of Agriculture [16]. In this study, straw from wheat, barley and oats are considered as a feedstock for ethanol production as these types of cereals are the most commonly cultivated in the region. These cereals made up nearly 97% of the total cultivation area for cereals in the region in 2009 [16].

The ethanol production potential in the region (B) is calculated for each cereal type (wheat, oats and barley) using Eq. (1):

$$B = \sum_{i=1}^{4} S_i Y_i R_i A Y_{EtOH} \qquad (1)$$

where B is straw-based ethanol production potential (MWh), S_i is the cereals cultivation area (ha), Y_i is the cereals yield in the respective county (kg/ha), R_i is the crop to residue ratio for each cereal type, A is the straw availability, Y_{EtOH} is the ethanol production yield from straw (litre/kg), and i is the type of cereal crop.

Input data for estimation of straw supply and ethanol production potential is presented in Table 1 and in the text below.

Table 1. Input data for straw supply in the Sala-Heby region, 2009.

Parameter	**Unit**	**Type of biomass**				**Reference**
		winter wheat	spring wheat	barley	oats	
$\mathbf{R_i}$	1	1.3	1.3	1.2	1.3	[17]
$\mathbf{C_i}$	tonnes/year	14 733	12 464	41 137	30 549	Based on data from [5,15]

* Cereals production, $C_i = S_i * Y_i$

Cereals production (C_i) is calculated based on cultivation areas and average yields for cereal crop production. Cereal yields (Y_i) for Sala and Heby municipalities correspond to average yields in the counties that the municipalities belong to. As a proportion of straw has to be ploughed back into the soil to maintain the soil fertility and avoid erosion, only about 57% by weight (A in Eq. 1) of the total amount of straw produced can be used for fuel production [17]. The energy content of pure ethanol is 6.24 kWh/litre [18].

The future straw supply in the region is analyzed for the following scenarios:

- Scenario 2020-P1 – all the parameter values remain the same except areas for cereals cultivation. The total straw production is assumed to increase by 20% through use of fallow land for ethanol straw cultivation. Fallow land currently accounts for 29% of arable land for cereals production in the Sala-Heby region.
- Scenario 2020-P2 – all the parameter values remain the same except the yield for ethanol conversion from straw, which is assumed to increase to 0.35 (litre/kg) (Y_{EtOH}) due to improvements in the process technology.
- Scenario 2020-P3 – combines scenarios 2020-P1 and 2020-P2.

2.1.2. Transport fuel demand

There is a lack of statistics on motor fuel usage at the municipal level. We calculate the average distance covered per car and average fuel consumption per kilometre driven, and therefore the use of motor fuel based on the number of passenger cars registered in the municipalities of Sala and Heby. Input data was obtained from Swedish Official Statistics [5, 19]. The Swedish Energy Agency is the state authority responsible for disseminating statistics in the field of energy use in transportation, and Transport Analysis (Trafa) produces statistics on vehicles types and distances covered. The development of passenger car use in Sala-Heby region is shown in Figure 2 (based on data from [19]).

Ethanol fuel demand in the Sala-Heby region (D) is estimated for E5 and E85 ethanol mixtures using Eq. (2):

$$D = \sum_{i=1}^{2} N_i S_i Q_i C_i E \qquad (2)$$

where D is estimated ethanol fuel demand (MWh), N_i is the number of vehicles in use during a year, S_i is the distance covered per vehicle in the respective county in a year (km), Q_i is the fuel consumption per type of fuel and kilometre driven in each county (litre/km), C_i is the ration of pure ethanol to petrol in each type of fuel blend used, and E is the energy content of the fuel (kWh/litre). For E5 fuelled passenger cars i=1, and for E85 fuelled passenger cars i=2.

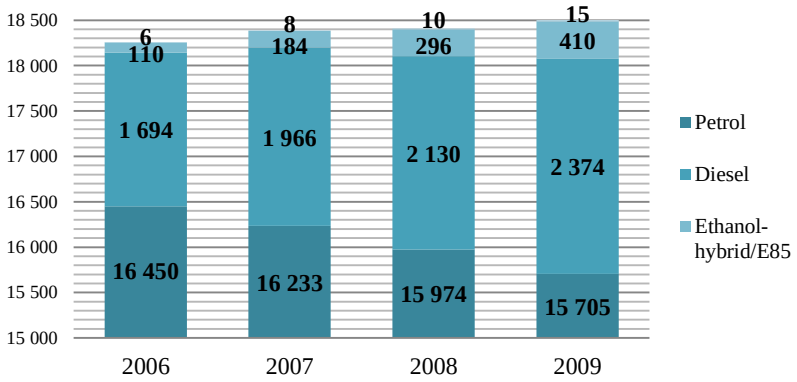


Fig. 2. Passenger cars in use by fuel type in 2006 -2009 in Sala-Heby. Based on data from [19].

It is assumed that all petrol fuel in the region is E5 fuel, as the share of low blend petrol in Sweden is 95% according to [3] and more detailed data on the regional share of E5 fuel and petrol fuel is not available.

To evaluate current and future regional demand on transport the following scenarios were analyzed:

- Scenario 2020-D1 – all the parameters remain the same except the numbers of passenger cars fuelled by petrol and ethanol fuels. The number of E85 fuelled cars increases and the number of E5 fuelled cars decreases, following the same trend as during the period 2006-2009 for each vehicle type. In this way, the total number of E5 and E85 fuelled vehicles is projected to be 17 814, a reasonable increase of 10.5% the 2009 figure.
- Scenario 2020-D2 – all the parameters remain the same except the amount of ethanol blended with petrol fuel, which is assumed to increase from 5% to 10% of the petrol fuel mixture, meaning that passenger cars are fuelled E10 with instead of E5. As in scenario 2020_1, the total number of cars is 17 814, following the trend in car numbers for the period 2006-2009. Petrol fuel consumption per driven kilometre is assumed to decrease following the trend from 2006-2009 (-1.2%), and is 0.074 l/km in 2020.
- Scenario 2020-D3 – this is the most extreme scenario, where it is assumed that all passenger cars are to be fuelled by E85 ethanol fuel.

2.1.3. CO_2 emissions from transportation

Estimates of CO_2 eq. emissions from passenger cars are based on the results presented by Johansson and Fahlberg [18]. Emissions rates in [18] and those presented in Table 2 are lifecycle based and include emissions from fuel combustion, production and distribution. The CO_2 eq. emissions factors on which further calculations are based are presented for E5, E85 and E10 (see Table 2).

Table 2. Total CO_2 eq. emissions factors by type of transport fuel [18].

CO_2 eq. emissions by type of fuel, (g/kWh)	
E5	277.48
E10	269.34
E85	110.54

3. Results and discussion

Regional straw production is estimated using Eq 1 and the input data presented in section 2.1.1. This calculation estimates 98 924 tonnes of straw in 2009. Thus, current straw-based ethanol production potential in Sala-Heby is 13 015 m^3 or 81 210 MWh as presented in Table 3 for 2009 and future Scenarios.

Table 3. Estimate of straw based ethanol production in Sala-Heby region.

Parameter	Unit	2009	2020-P1	2020-P2	2020-P3
$B_{ethanol}$	MWh/year	81 210	97 452	98 012	117 615

Regional ethanol fuel demand is estimated using Eq. 2 and the assumptions from the scenarios presented in section 2.1.2., and is presented in Table 4.

Table 4. Estimate of ethanol fuel demand in Sala-Heby region. Parameters for year 2009 are input parameters obtained from statistical databases and reports. Values in bold are changed from 2009.

Parameter	Unit	2009	2020-D1	2020-D2	2020-D3	Reference
N_1	1	15 705	**13 251***	13 251	**0**	[19]
N_2	1	410	**4 563****	4 563	**17 814**	[19]
S_1	km	14 267	14 267	14 267	14 267	[19]
S_2	km	14 267	14 267	14 267	14 267	[19]
Q_1	l/km	0.084	0.084	**0.074**	not relevant	
Q_2	l/km	0.126	0.126	0.126	0.126	[18]
C_1	1	0.05	0.05	**0.1**	not relevant	
C_2	1	0.85	0.85	0.85	0.85	
E_1	kWh/litre	8.598	8.598	8.474	8.598	[18]
E_2	kWh/litre	6.612	6.612	6.612	6.612	[18]
$D_{ethanol}$	MWh/year	12 234	52 927	57 955	179 977	-

*Average annual decrease in petrol fuelled passenger cars is 1.5%. Based on this rate the number of E5 fuelled passenger cars is estimated at 13 251.
**Average annual increase in E85 fuelled cars during 2006-2009 is 39%, whereas assumed average increase after 2014 is 20%. It is assumed to be unlikely that the early increase of 39% is maintained until 2020.

Distance covered per car and year for the whole Sala-Heby region is calculated from weighted averages of distances covered per car and year in each municipality. Distances covered by car in each municipality are obtained from [19] and are assumed to remain the same over the study period. Fuel consumption per driven km is assumed to decrease following the same trend as 2006-2009. E85 fuel consumption (Q_2) is assumed to remain the same. In scenario 2020-D2 E10 fuel is assumed to be used (C_1=0.1). For Scenario 2020-D2, the energy content of the fuel (E_1) corresponds to the energy content of the E10 ethanol mixture based on the assumption made for this scenario.

Summarized results for straw based ethanol supply and ethanol demand are presented in Figure 3. These figures indicate that the regional transport system can become self-sufficient in ethanol fuel by implementing local small ethanol production from locally produced cereal straw. The system could become fossil fuel free by 2020 using this approach.

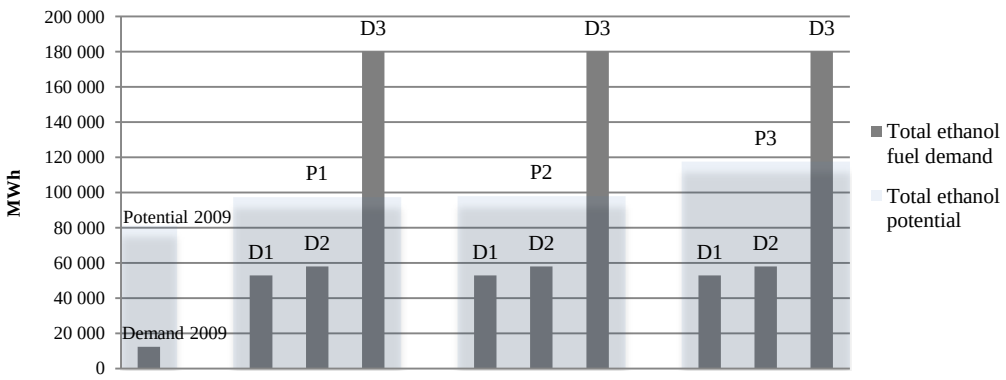


Fig.3. Ethanol supply potential and ethanol fuel demand in the Sala-Heby region (MWh).

The CO_2 eq. emissions from passenger cars were estimated (see Table 5), based on the same scenarios and approach as for the estimate of the ethanol fuel demand (see section 2.1.2.). Current CO_2 eq. emissions from transport are 45 446 tonnes. Assuming that the number of passenger cars in the region continues to increase according to the trend of the last 5 years, and assuming that all cars will run on E85 in 2020, the total CO_2 eq. emissions can be reduced to 23 591 tonnes CO_2 eq., a reduction of 21 855 tonnes CO_2 eq. or 48% from 2009.

Table 5. Estimate of CO_2 eq. emissions from passenger cars in Sala-Heby region.

Parameter	2009	2020-D1	2020-D2	2020-D3
Total CO_2 emission from passenger cars fuelled by petrol and ethanol fuel, tonnes	45 446	43 930	38 938	23 591

Börjesson [8] studied the reduction of GHG emissions obtained from using ethanol instead of petrol, including GHG emissions from producing ethanol. Using wheat grain based ethanol produced in Sweden results in an 80% GHG emission reduction compared to petrol fuel, while ethanol from Brazilian sugarcane gives 85% emission reduction [8]. Börjesson concluded that the results are very much dependent on the structure of the individual system. Assuming some different scenarios for the type of cultivation land, use of by-products from ethanol production, the reduction of using ethanol from current production in Sweden can be as low as 55% [8]. This paper focuses on GHG emission savings from road private traffic if replacing current petrol use with locally produced straw based ethanol assuming different scenarios for future car fleet development and ethanol supply. The CO2 eq. emission factors presented in [18], on which the calculations in this paper are based, correspond to 76% total CO2 eq. emission savings for pure ethanol compared with pure petrol fuel.

4. Conclusions

This study shows that the available cereal straw in the studied region is sufficient to meet local ethanol demand for 2009. However, it is not sufficient for a scenario where all passenger cars are fuelled with E85. If passenger car numbers increase according to the current trend until 2020, 3% CO_2 eq. emissions reductions can be achieved by using locally produced ethanol from cereal straw. CO_2 eq. emissions can be reduced by 14% by replacing all petrol fuel with fuel containing 10% ethanol (E10 fuel), and by 48% if all passenger cars in the studied region use E85 fuel.

This paper analyzes how the regional energy system can contribute to reducing CO_2 eq. emissions by realizing local small scale bioethanol production and substituting petrol with ethanol fuels in road transportation.

References

[1] Directive 2009/28/EC of the European Parliament and the Council of 23 April 2009 on the promotion of the use of renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC

[2] Energy Indicators 2008. Theme Renewable Energy, Swedish Energy Agency, Report ET2008:21, Västerås, 2008, 97 pp.

[3] Energy Use in Transport Sector - 2009, Swedish Energy Agency, Report ES2010:04, Eskilstuna, 2010, 28 pp.

[4] Energy Use in Transport Sector - 2008, Swedish Energy Agency, Report ES2009:04, Eskilstuna, 2009, 24 pp.

[5] Statistics Sweden (SCB), 2010 - http://www.ssd.scb.se/databaser/makro/start.asp

[6] Swedish Energy Agency, Report ER 2009 27 (in Swedish), "Kvotpliktsystem för biodrivmedel - Energimyndighetens förslag till utformning", Eskilstuna, 2009

[7] European Environment Agency (EEA), October 2008

[8] Börjesson P., Good or bad bioethanol from a greenhouse gas perspective – What determines this?, Applied Energy, Vol. 86, Issue 5, pp. 589-594, 2009

[9] Starfelt, F., Thorin, E., Dotzauer, E., Yan, J. Performance evaluation of adding ethanol production into an existing combined heat and power plant, Bioresource Technology, 101 (2010) pp. 613–618

[10] A. Wingren, M. Galbe and G. Zacchi, Energy considerations for a SSF-based softwood ethanol plant, Bioresource Technology, 99 (2007), pp. 2121–2131

[11] Seabra, J., Tao, L., Chuma, H.L., Macedo, I. C. A techno-economic evaluation of the effects of centralized cellulosic ethanol and co-products refinery options with sugarcane mill clustering, Biomass and Bioenergy, 34 (2010), pp. 1065-1078

[12] Ou, X., Zhang, X., Chang, S. Scenario analysis on alternative fuel/vehicle for China's future road transport: Life-cycle energy demand and GHG emissions, Energy Policy, 38 (2010), pp. 3943-3956

[13] Papagiannaki, K., Diakoulaki, D., Decomposition analysis of CO_2 emissions from passenger cars: The cases of Greece and Denmark, Energy Policy, 37 (2009), pp. 3259-3267

[14] Upplands lokaltrafik, personal communication, 2010

[15] Västmanlands lokaltrafik, personal communication, 2010

[16] Swedish Board of Agriculture, 2010 - http://statistik.sjv.se/

[17] Johansson, J., and Lundqvist, U. Estimating Swedish biomass energy supply. Biomass and bioenergy, 1999; 17(2): 85-93

[18] Johansson, S., Fahlberg, K., 2009, Methods for strategies and assessment of climate change mitigation initiatives at local and regional levels, Emission Factors – Statistical Datasheet, http://www.ima.kth.se/klimatswe/html/rapporter.htm

[19] Transport Analysis, Trafa, 2010 - http://www.trafa.se/Publikationer/