AUTONOMOUS FREIGHT TRAINS IN AUSTRALIA

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Abstract
Australia's first autonomous train began running in July 2018. Its running was preceded by extensive trials of both on- and off-train technology. It was not a classic metro train but a 30,000+ tonnes bulk iron ore train, comprising 220-240 wagons, each weighing 130-160 tonnes when laden, and hauled by 2x3280 kW diesel locomotives. This paper discusses the usual rationales for developing autonomous trains and then tests them against the realities of running heavy haul freight trains in remote areas. Any theoretical lack of line capacity is less important than the need for reliable mine-to-port supply chains. Furthermore, mining in remote areas is expensive and increasingly difficult to resource so automation of processes is increasingly attractive to mining companies. The automation of iron ore railway operations beckoned if mining companies could assemble, test and have accepted the various technical building blocks. Pilbara Iron has now completed these steps.

Keywords
Autonomous Trains, Freight Trains, Heavy Haul Railways, Driver Advice Systems

1 Introduction

Australia's first autonomous train began running in July 2018. See Hastie (2018). Its running was preceded by extensive trials of both on- and off-train technology. It was not a classic metro train but a 30,000+ tonnes bulk iron ore train [1], comprising 220-240 wagons, each weighing 130-160 tonnes when laden, and hauled by 2x3280 kW diesel locomotives. The operator was Pilbara Iron, owned by multi-national miner Rio Tinto. Pilbara Iron's railway runs between two ports, Dampier and Cape Lambert, and multiple mines (approximately 13) in Western Australia's Pilbara region. Its principal mainline runs between the Dampier port and the Paraburdoo mine for a distance of roughly 380 kilometres with mines on some branch lines being up to 440 kilometres distant from a port. Figure 1 shows the general Pilbara locality, its ports, mines, railways and roads.

This paper discusses the whys and hows of Australia's first autonomous train running on a freight railway.

2 A General Background to Autonomous Trains

There has to be a rationale for adopting autonomous trains in preference to running manually operated trains. Typically, a railway might turn to autonomous operation if it needed to increase its throughput beyond what might be possible under manned operation. Because line capacity is a key railway asset, increasing it should increase the numbers of passengers or the amount of freight that could be carried over some reference time period.

However, there will always be limiting factors. Braking distances with respect to maximum permitted speeds generally determine how close trains may run together, either at their free speed or at a restricted speed when closing on preceding trains. On the other hand, any perturbation in the train flow will also reduce the effective train flow. While autonomous operation can eliminate the variability of manual operation, it cannot deal with sources of train flow perturbation that are not related to train driving, such as from station dwell times on passenger railways or junction delays on passenger and freight railways.

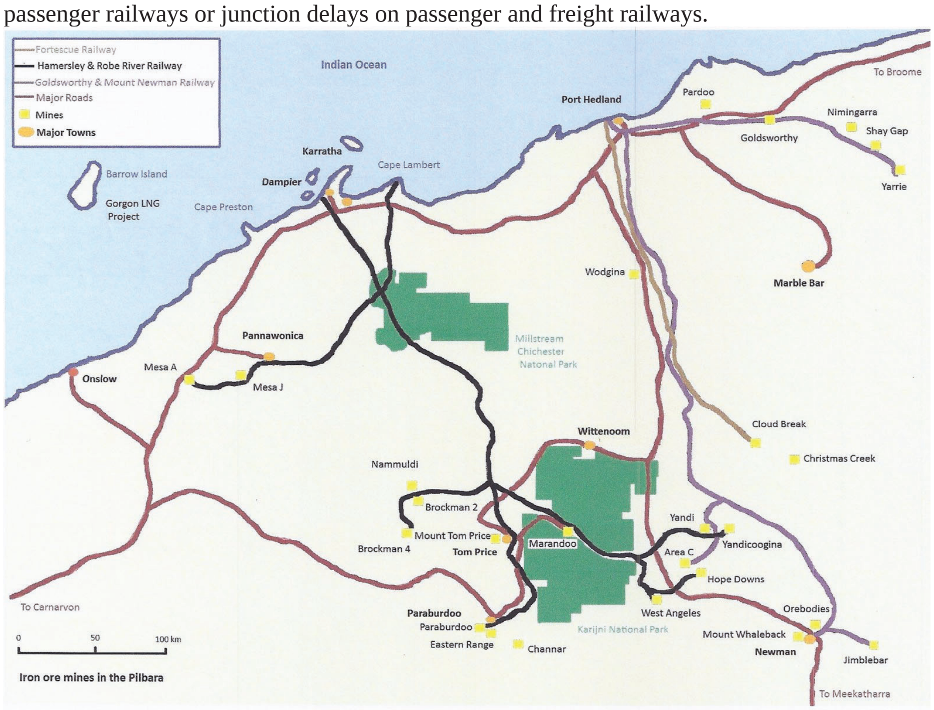

Figure 1: Locality Map of the Pilbara Region of Western Australia

Passenger or commodity flows can be increased without increasing train flow if train sizes can be increased. Trains can be lengthened and/or the carrying capacity of carriages or wagons can be increased. However, at some stage, train size must reach its limit.

There are physical and operational constraints that must be respected. For example, passenger trains have to fit inside limiting platform lengths. Growth in the numbers of passengers being transacted through limiting stations will lengthen station dwell times until train flows are then reduced. The controlling factors are different for freight trains. Increased train weight will eventually exceed the haulage capabilities of their locomotives. Growing train length will eventually debase train braking until increased length is not commercially viable [2]. In any case, infrastructure constraints affect all types of trains.

Nevertheless, passenger railways are more likely to be the beneficiaries of autonomous operation than freight railways because they are more likely to reach their line capacity limits, particularly during urban peak periods, and rarely have the option of increasing train size.

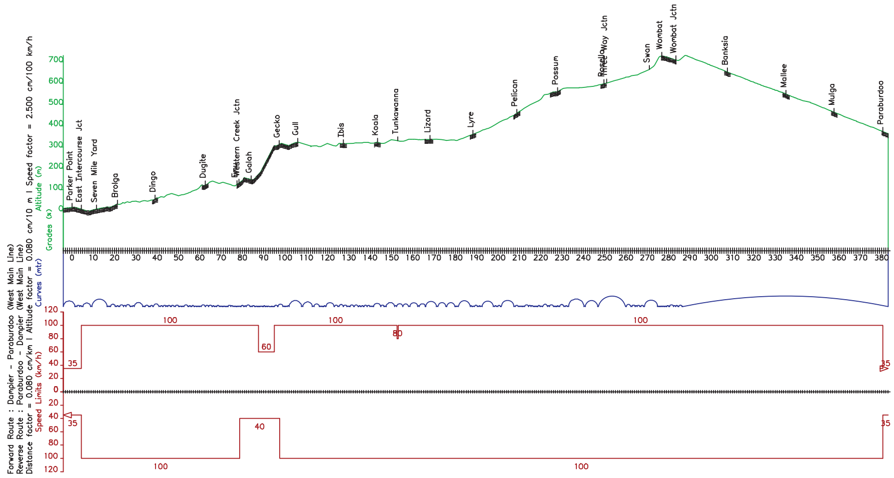

Figure 2: Vertical Profile of the PIRD Mainline between Dampier and Paraburdoo [3]

3 Line Capacity Issues on the Pilbara Iron Rail Division (PIRD)

To address the question of whether line capacity is an issue, I analysed the capacity of PIRD's 2006 mainline network, based on data collected during a 2005 field trip to the Pilbara region. Pilbara Iron then operated two ports: Dampier and Cape Lambert. Originally, Hamersley Iron (HI) ran from Dampier to its Tom Price and Paraburdoo mines while Cliffs Robe River Iron Associates (CRRIA) ran from Cape Lambert to Pannawonica. Eventually, through acquisitions and merger into Pilbara Iron, the two port, railway and mining concerns were connected via a link between Western Creek on the CRRIA mainline and Emu on the HI mainline. Now all mines southeast of the Chichester Range can flexibly dispatch iron ore to either port. By 1978, HI had already duplicated its Chichester Range crossing between Emu and Gull to provide operational flexibility on this difficult stretch of railway with its 2% grade against empty trains, as can be seen in Figure 2. See Hamersley Iron (1978). This gradient also dictates the maximum empty train weight and hence the maximum laden train size.

In 2005, PIRD was steadily extending mainline duplication from Gull to Tunkawanna and onwards to Rosella. PIRD deployed automatic signalling to separate following trains on double track sections and the longer single track sections. The shorter single track sections were absolute block sections. Originally, HI and CRRIA provided wayside signals to control trains. However by 2005, many of the HI sections were controlled by cab signals with automatic train protection (ATP) [4]. Centralised traffic control was superimposed over the signalling to direct trains into and out of crossing loops and over crossovers on bi-directional double track, although trains would normally take the left hand track on double track, as in the rest of Australia.

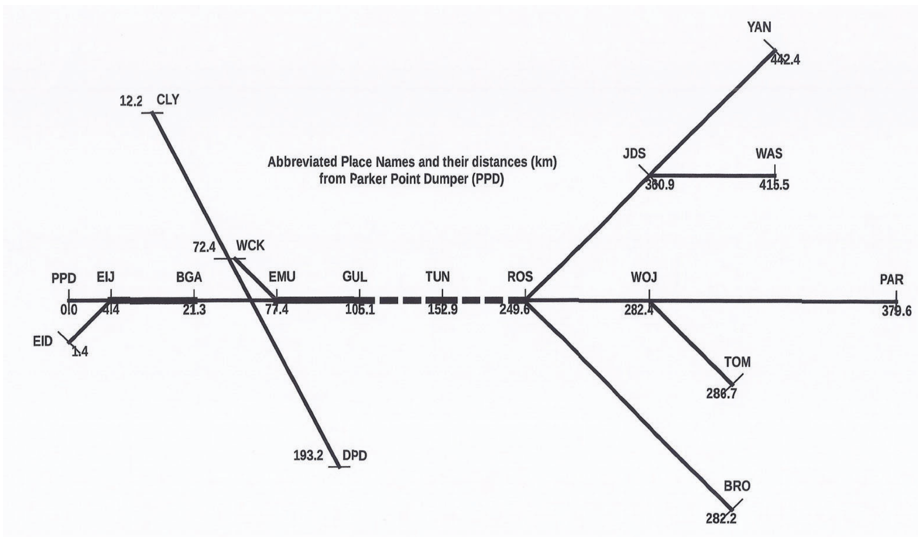

Figure 3: Schematic Network Diagram of PIRD Operations circa 2006

A static capacity analysis of PIRD's operations is presented in Table 1 (refer to Figure 3 for a schematic network diagram). In calculating line capacity, single track and double track sections need to be treated differently. In single track sections, sectional running times for opposing trains plus their respective sectional clearance times are needed to calculate the theoretical capacity for a two-way train flow. In double track sections, the minimum times for trains to clear each signal block joint to its corresponding limit of authority must be calculated to estimate theoretical capacity in each direction of travel. In general, block lengths, like crossing loop siding lengths, are sufficient for a train to stop from a line speed of typically 75 km/h. However, stopping distances are always affected by gradients. The 2% gradient down the Chichester Range is a significant impediment to laden trains, requiring trains to maintain a downhill speed of no greater than 40 km/h (see the bottom speed limit trace in Figure 2).

In 2006, three duplication projects were being considered in the Emu to Rosella section:

- the original Emu to Gull section;
- the then recently completed extension from Gull to Tunkawanna; and
- the intended extension from Tunkawanna to Rosella, the junction for two branch lines.

It can be seen that progressive duplication of the trunk Emu to Rosella section would eventually reduce theoretical line capacity utilisation from nearly 60% to less than 15% with an expected improvement in operational reliability. This is because high utilisation levels are inevitably accompanied by exponentially increasing delays, the more so on single track railways than on double track railways. See Jones & Walker (1973).

Table 1: Static Capacity Analysis of PIRD Operations circa 2006

Line Section *(Refer to Figure 3 for locations)*	**Len** *(km)*	**Single Track** *Dir*	*Cap* (t/d)	*Dmd* (t/d)	*Utl* (%)	**Double Track** *Dir*	*Cap* (t/d)	*Dmd* (t/d)	*Utl* (%)
East Intercourse Jctn (EIJ)-Brolga (BGA)	16.9	1W				OB	465	16	3
		1W				IB	129	13	10
Brolga (BGA)-Emu (EMU)	56.1	2W	61	29	48				
Cape Lambert (CLY)-Emu (EMU)	65.2	2W	46	6	13				
Emu (EMU)-Gull (GUL)	27.7	1W				OB	116	20	17
		1W				IB	117	15	13
Gull (GUL)-Tunkawanna (TUN)	47.8	1/2W	59	34	58	OB	140	20	14
						IB	133	15	11
Tunkawanna (TUN)-Rosella (ROS)	96.7	1/2W	59	32	54	OB	127	18	14
						IB	133	15	11
Rosella (ROS)-Juna Downs (JDS)	111.3	2W	28	15	54				
Rosella (ROS)-Wombat Junction (WOJ)	32.8	2W	49	11	22				
Rosella (ROS)-Brockman (BRO)	32.6	2W	38	6	16				

Notes:
1. Direction of travel (Dir) is either 1-way (1W) outbound from the ports (OB)/inbound (IB) to the ports or 2-way (2W).
2. Theoretical sectional capacity (Cap) has been calculated for a 24-hour period.
3. Actual sectional demand (Dmd) has been obtained from a nominally 25 trains/day timetable.
4. Utilisation (Utl) is the percentage of theoretical capacity consumed by actual demand.

Parallel dynamic capacity analyses, using the SKETCH model, were then undertaken to determine the minimum operational delays that would be visited on an optimal nominal 25 trains per day timetable for the different infrastructure scenarios. For its mathematical basis, see Pudney & Wardrop (2004). Duplication of only the Emu to Gull section would yield a minimum average delay of 13% of bare sectional running times. Extending the duplication from Gull to Tunkawanna would only reduce the minimum average delay to 12%. However, completing the duplication from Tunkawanna to Rosella would drive the minimum average delay down to 7%.

Real railways cannot operate with such theoretical delays. Typically, real operating delays would be double theoretical delays. For example, iron ore railway experience in the Pilbara suggests that real delays would be roughly 20% of bare travel times (see Figure 4 for historical data on the variability of components of HI's train cycle times). Infrastructure changes, such as complete duplication between Emu and Rosella, would thus induce an acceptable level of operational reliability into the mine-to-port supply chain.

Taking into account the above static and dynamic capacity analyses, PIRD operations are clearly not running close to line capacity. Furthermore, any emerging limiting sections are now likely to be branch lines to the mines or to the ports. In both instances, conventional single line section division or duplication would deliver requisite line capacity improvements. Therefore, autonomous train operations are not being pursued on line capacity grounds.

4 Train Size Issues on PIRD

Early Pilbara railway developments from the late 1960s followed contemporary North American practice, including axle loads of the order 32.5 tonnes for locomotives and wagons. Thus, 6-axle locomotives typically weighed up to 196 tonnes in working order and 4-axle ore wagons weighed up to 130 tonnes fully laden. All else being equal, drawgear capacity, locomotive power and the action of direct-release air brakes were the limiting factors. Early trains were hauled by 3x2700 kW locomotives (and were banked by three more locomotives for the first 100 km) and grossed 23,000 tonnes. Since then, much effort has gone into training drivers to avoid breaking drawgear as train weight and length were increased.

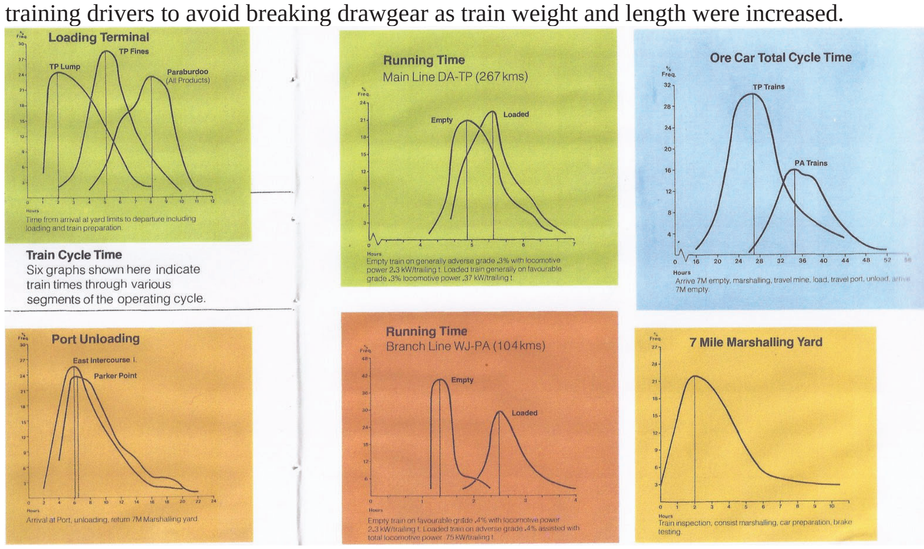

Figure 4: Components of HI's 1978 Train Cycle Times

The original track plant, based on 59 kg/m rail on timber sleepers, proved to be inadequate for trains comprising the above rolling stock, so it was gradually replaced with conventional 68 kg/m rail and closer-spaced timber sleepers. Given the steady increase in annual tonneage, the track plant has since been upgraded to head-hardened 68 kg/m rail and concrete sleepers.

Progressive improvements in train technology have lead to the adoption of roughly 3280 kW locomotives with higher factors of adhesion, so that trains can now gross over 30,000 tonnes. Behind these statistics are improvements in locomotive and train braking. Locomotives now have extended range dynamic brakes and wagons are now fitted with ECP brakes [5]. The adoption of locomotives with ac traction motors offers further scope for operational improvement. However since the major haulage task is predominantly downhill, braking performance, rather than starting tractive effort, is probably more important. Since SD70ACe (EMD) and ES44ACi/ES44DCi (GE) locomotives entered service from the mid 2000s, there have been no significant changes in train size on the original iron ore railways.

However, the recent mining entrant, FMG, directly adopted 40 tonne axle load wagons and built loading and unloading infrastructure to match. This encouraged the established miners to also move towards 40 tonne axle load ore wagons. However, larger wagons still have to fit through existing wagon dumpers [6].

The conclusion that can be drawn is that PIRD's train size has plateaued within locomotive tractive effort and drawgear constraints. The only way to haul more iron ore is to run more trains, needing more drivers.

5 The Pilbara Mining Back Story

The way mining is carried out in remote areas is the key to understanding PIRD's move towards autonomous trains.

The Pilbara region is roughly two hours flying time from Perth, already one of the world's most remote cities. The cost of labour weighs heavily on mining, especially for low value, high quantity commodities, such as iron ore. Originally, the mine workforce lived on site in the Pilbara. However increasingly, resident employees are being converted to fly-in-fly-out (FIFO) employees [7] because companies can save accommodation costs by placing them in short-stay camps.

Large quantities have to be mined and shipped to distant customers. Large quantities require matching infrastructure, such as:

- ocean ports capable of handling ships up to 320,000 DWT;
- sufficient berths to handle such ships for different miners;
- stockyards behind the berths for cargo assembly;
- wagon unloaders and conveyor runs to feed the stockyards;
- railway lines bringing laden trains into each port;
- a range of mines to exploit different ore bodies and to facilitate ore blending to create a consistent iron content; and
- wagon loaders to efficiently place ore in trains.

Consequently, unit costs of production, including the amortisation of this entire infrastructure, have to be driven down. Therefore, mining and transportation costs are being attacked through automation.

Train loading and unloading were early candidates for automation. Train loading can be carried out by hauling trains at a fixed low speed under bins or through load-out tunnels, usually without a driver. Alternatively, empty trains can be indexed [8] under bins, without attached locomotives. All laden trains in the Pilbara are emptied by being indexed through tipplers, without attached locomotives.

Pilbara Iron led the way with the early automation of ore haulage from the mine face to the train loader. This was to reduce costs, introduce electrification of the haulage trucks and to improve mine safety by avoiding haul road accidents. Some miners are even taking automation directly to the mine face. See Lucas (2018).

PIRD has been pursuing mainline railway automation, not specifically to increase throughput, but to provide itself with train scheduling flexibility. The rostering of mainline train drivers was quite rigid to ensure that drivers could be employed productively. Amongst other practices, drivers were rostered to swap in the field between outbound empty trains and inbound laden trains, so that they could work out-and-back from a home location. If trains could not be despatched on time, for whatever reason, drivers' shifts could be wasted.

The clear object of the automation of mainline train operations was to be able run trains when they were ready and then to run them straight through from port to mine or vice versa, subject only to the usual traffic delays. There would still be a need for manual locomotive driving to position trains for loading and unloading, to fuel and provision locomotives and to move locomotives or wagons to and from maintenance and repair facilities.

6 Requisite Steps for Automating Mainline Train Operations

It is important to understand that PIRD's trains are autonomous, rather than remotely controlled. Thus, they need an on-board intelligence to be able to drive themselves within their limits of authority and within prevailing geographic constraints of gradients, curvatures and speed limits. Their progress would be monitored but they realistically could not be remotely driven, because the problems of rostering drivers would then be transferred from the field to a central office.

There appear to be a number of actions (although not an exhaustive list because PIRD have not disclosed their actual implementation) that had to be undertaken prior to running an automated mainline railway:

- provision of direct communications between a remote control office and each train;
- location of each train to be determined by GPS;
- provision of forward-facing CCTV and proximity sensors on each train with a continuous feed back to the control office;
- setting of each train's route from the control office;
- setting of each train's limits of authority from the control office and/or local automatic signalling and delivering these limits of authority to each train;
- delivering approaching track alignment and speed limit knowledge to each train;
- development of suitable driving control systems;
- control of traction and dynamic (electric) and air braking on each train; and
- provision of precise control of air brakes down the length of each train.

PIRD was an early adopter of centralised traffic control, whereby routes could be remotely set throughout its mainline network. Limits of authority were initially set by wayside signals, but these have been progressively replaced by cab signals, whose aspects can be transmitted to trains via coded track circuits. The control office, as well as the passage of trains, can set home signals (or their equivalent). The passage of trains alone can set automatic signals. Originally, the control office was adjacent to PIRD's mainline near Karratha. Nowadays, it is located in Rio Tinto's Perth offices.

Track circuiting provides positive detection of the presence and absence of trains but cannot precisely locate trains. However, coded track circuits, as adopted by PIRD, can continuously provide trains with their limits of authority, in a wholly distributed manner. GPS can continuously locate trains, but not to a precision that can prevent collision.

Geographic knowledge can be transmitted to trains in a number of ways [9]. In PIRD's case, alignment data is transmitted en route through passive on-track balises. The alignment data is then assembled on board the train so that driving calculations could be made to manage the train. Initially, PIRD used the alignment data to calculate the ATP braking trajectory that each train would run within, as it was reaching the limit of its current authority. However with autonomous train operation, complete power, hold, coast and/or brake trajectories must be calculated by the on-board driving control systems. See Albrecht et al (2016) for the basis behind optimal train control.

The driving of long and heavy freight trains, such as PIRD's ore trains, not only has to continually set the train's operational mode (ie power, hold, coast or brake), but also has to handle in-train forces. A long-standing problem with iron ore trains, particularly those with direct release air brakes, was the creation of force shock waves running backwards and forwards along the length of a train. If these forces became too intense trains would break apart. PIRD accordingly developed a driving simulator to train its drivers in the appropriate handling of long trains. Thus, long trains had to be kept stretched under traction and braking to avoid running in and out and generating shock waves along the train.

While long freight trains were fitted with direct release air brakes [10], control of in-train forces was an issue that was only handled by drivers with route knowledge, reinforced with simulator training. This was an impediment to automated driving because of the need to continuously estimate the magnitude of in-train forces and then manipulate the air brakes to keep the train stretched. There was also the issue that classic air brakes took a significant time to apply and release because of the speed at which service brake applications propagated down the length of a train.

However, PIRD has now fitted ECP to its ore trains. ECP allows air brakes to be graduated on and off, simultaneously down the length of a train, while keeping the train stretched train. Dynamic braking now supplements air braking when a train's downhill speed needs to be held against a grade, rather than vice versa with direct release air brakes.

The installation of ECP was an important step towards implementing automated train driving. It allowed all directional, traction and braking decisions to be made by driving control systems. When complemented by electronically available alignment data and limits of authority, all the technical building blocks for running autonomous trains were now available.

7 Running Autonomous Trains in Remote Areas

The Pilbara region of Western Australia is semi-arid and sparsely populated. Various iron ore railways pass from the Indian Ocean coast to the highlands where much of the region's iron ore is mined. The railways are unfenced, are typically paralleled by gravel access roads, are crossed by watercourses and are intersected by road/rail level crossings, most of which are only passively protected. Cattle and native animals may venture onto railway reserves in search of feed. People in cars and trucks often drive along the access roads and cross the railways in their travels. There is an ever present, but low, risk of collision (more likely with intruders than other trains), irrespective of whether trains are manually or automatically driven. By their nature, trains can warn intruders but cannot take evasive action.

The biggest non-technical issues for running autonomous trains are the detection and mitigation of accidents when trains break down, collide or derail. PIRD already runs a highly instrumented railway to identify train health issues before they lead to failure. However, such measures cannot detect collisions with people, road vehicles, landslides or washouts. PIRD will have placed detection devices, such as CCTV and presence detectors, on board its autonomous trains, not so much to avoid collision, as to detect it.

There is still the need to physically respond to incidents that stop autonomous trains. The issue with autonomous train operation will be how long it will take the central office to be aware of an incident. Necessarily, response times to reach failed trains will still be long and the means of recovery will still be variable. However, the commercial pressures of maintaining the mine-to-port supply chain mean PIRD will have to evolve suitable processes from those already in place for manned train operations.

8 Conclusions

PIRD's pursuit of autonomous mainline railway operations has been long and deliberate and should be seen in the context of a general automation of mining, particularly in remote areas for which it is difficult to recruit suitably skilled employees. In itself, the running of autonomous trains will not immediately lead to running more trains. However, the combination of remote train despatching and on-board driving control systems should lead to better timekeeping of individual trains, better control of train flows and more intense use of the railway.

PIRD gradually assembled the technical building blocks of:

- centralised and remote route setting;
- the setting of limits of authority for individual trains;
- implementation of competent ATP;
- conversion of train air brakes to ECP; and
- development of on-board driving control systems and their integration with locomotive control systems.

Actual field-testing and the regulatory authorisation of autonomous train operation took more time. Now autonomous trains are running in revenue service. The exciting future prospect is that what has been applied on remote heavy haul freight trains could also be applied to suburban passenger trains.

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End Notes

1. While there have been autonomous trains since the 1920s, the British Post Office railway under central London being a notable example, it is most likely that the first large autonomous freight train ran on the Black Mesa and Lake Powell Railroad in 1973. This train hauled coal between a mine and a power station in a closed operation, using remotely controlled electric locomotives.
2. On 21 June 2001 BHP Iron Ore ran the largest ever freight train, grossing 99734 tonnes and extending 7300 metres, between Yandi and Port Hedland in the Pilbara (See Railway Gazette 1 August 2001). However, train traction and braking was unstable, notwithstanding multiple locomotives being distributed throughout its length.
3. The grading line is shown in green, the heading line is shown in blue, the distance baseline (in kilometres) is shown in black and directional speed limits are shown in red. Crossing loops and duplicated track are highlighted as black bands under the grading line.
4. Block sections were rationalised under cab signalling to reduce the wayside plant. The combination of static balises, to provide track geometry data, and signal aspects via coded track circuits, to give the limits of authority, allowed trains to calculate their braking trajectories over long sections to each limit of authority.
5. Electronic Control of Pneumatic brakes (ECP) is a freight train air brake technology, which permits air brakes to be simultaneously applied or released in a graduated manner down the length of a train, regardless of length.
6. Pilbara practice is to rotate wagons (tipple) to empty them because they are simple gondolas without bottom doors. The tipplers were built to handle wagons of fixed lengths. Typically, pairs of wagons are inverted to dump the ore into under-track hoppers with the ore being carried away by conveyors to stockpiles.
7. Fly-in-fly-out (FIFO) is a remote employment practice whereby employees are flown from their homes, say in Perth, to a mine, say Yandicoogina, and employed for, say, two weeks straight on long shifts before being flown home to rest for one week.
8. An indexer is a lineside mechanism, which accurately steps a train of wagons, one or two wagons at a time, through a loader or unloader.
9. As an example, TTG's Energymiser train driving advice system downloads complete alignment data for a journey, which is then consumed during that journey.
10. Note that on PIRD single-pipe direct release air brakes were fitted, whereby auxiliary brake reservoirs were recharged over the same pipe as the air pressure braking signals were sent, so that recharge and application had to take place sequentially.