

FREIGHTMISER: AN ENERGY-EFFICIENT APPLICATION OF THE TRAIN CONTROL PROBLEM.

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ABSTRACT

Fuel costs and CO₂ emissions are a major concern for all transport operators, and the rail freight industry must increase its efficiency if it wishes to remain competitive. *Freightmiser* is an in-cab advice system that helps drivers of long-haul trains save fuel and stay on time. *Freightmiser* uses optimal control theory to determine speed profiles that minimise fuel consumption subject to completing the journey within the specified time. The recommended speed profile is displayed on a screen in the cabin of the locomotive along with additional advice about track topography and train location that will assist the driver to follow an energy-efficient speed profile and stay on time.. The system determines current location and speed from an on-board GPS unit and continually updates the displayed advice during the journey, thereby ensuring that allowance is made for previous departures from the recommended speed profile. Thus the in-cab display always provides an optimal speed profile from the current position to the next target location. *Freightmiser* technology can ensure that best driving practice becomes the norm and hence consistently reduce fuel costs by as much as 15%.

Key words: train control, optimal strategies, energy – efficiency, fuel saving.

1. INTRODUCTION

Freightmiser is an in-cab system that displays information that helps long-haul train drivers stay on time and use less fuel. The system was developed by the Scheduling and Control Group at the University of South Australia and TMG Rail Technology with funding from the Australian Cooperative Research Centre for Railway Engineering and Technologies.

The main *Freightmiser* display is shown in Figure 1. The screen is divided into three areas:

1. **Route information.** The bottom half of the display shows track elevation, track curvature, and trackside features such as level crossings, signals, kilometre posts and crossing loops, for 6 km in front of the cab and 2 km behind the cab. The location of the train is indicated by the white line superimposed on the elevation profile. The vertical white lines indicate the front and rear of the train. Drivers find the route information useful because it shows the location of the front and rear of the train relative to hills, curves and speed restrictions, and because it provides confirmation of the train's location.

2. **Ideal speed profile.** The part of the display immediately above the route information shows the ideal speed profile calculated by *Freightmiser*. The height of the thick line indicates the ideal speed. The colour of the line indicates how much power is required to follow the ideal speed profile: green is full power, white is coasting, and red is braking. The thin orange line above the ideal speed profile indicates the track speed limit, including any temporary speed restrictions. The two white triangles indicate the current speed of the train, as measured by a built-in GPS unit. Whenever possible, the driver should drive so that the two triangles straddle the ideal speed profile.

3. **Destination.** The top strip of the display shows the current destination and the estimated time of arrival. The seven coloured blocks indicate which of seven possible speed profiles is being followed, from the least efficient speed profile (red) to the most efficient speed profile (green).

The screen is touch sensitive. The driver can touch the destination indicator to bring up a menu of alternative destinations. The driver can also use the "Earlier" and "Later" touch-screen buttons to select a faster and less efficient profile with an earlier arrival time or a slower and more efficient speed profile with a later arrival time. The estimated time of arrival is updated accordingly.

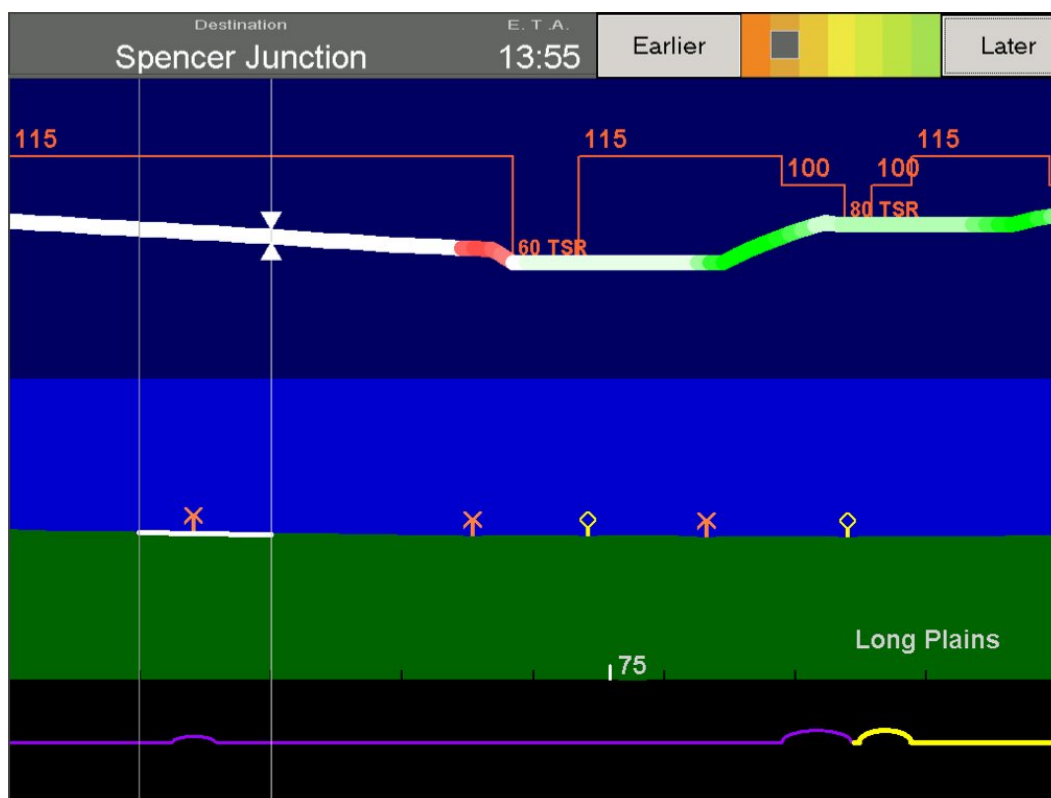


Figure 1: The main *Freightmiser* display

At the beginning of a trip, the driver must specify information that is used to calculate ideal speed profiles, including:

- the number and types of locomotives;
- the type of train (used to determine which speed restrictions apply);
- the length of the train;
- the mass of the train;
- the maximum permissible speed of the train; and
- the route.

This information can be selected from menus on the touch screen. Alternatively, this information could be automatically downloaded from a central server. Temporary speed restrictions are automatically downloaded from a central server over a wireless data network.

Destinations are key locations along a journey where the train has a specified arrival time. Destinations could be crossing loops where the train will pass or overtake another train, key junctions, crew change locations, or terminals.

Each time the driver selects a new destination, *Freightmiser* calculates seven optimal driving strategies from the current location of the train to the destination. Each of the seven profiles has a different arrival time. The fastest profile has the earliest arrival time, but uses the most energy to complete the journey. Each of the subsequent six profiles uses less energy than its predecessor, but takes more time.

Freightmiser speed profiles save fuel by:

- cruising at speeds less than the speed limit, if time allows;
- coasting; and
- reducing the amount of braking, particularly at high speeds.

The method used to calculate the ideal speed profiles is described in the next section.

The display changes slowly during the journey. It takes more than 5 minutes for a track feature to move across the screen. During a journey, drivers glance at the display every few minutes to check the progress of the journey and to see what control changes may be approaching.

At the end of each journey, *Freightmiser* uploads a journey log to a central server using wireless networking. The figure below shows a graph produced from a *Freightmiser* journey log for a 300 km journey.

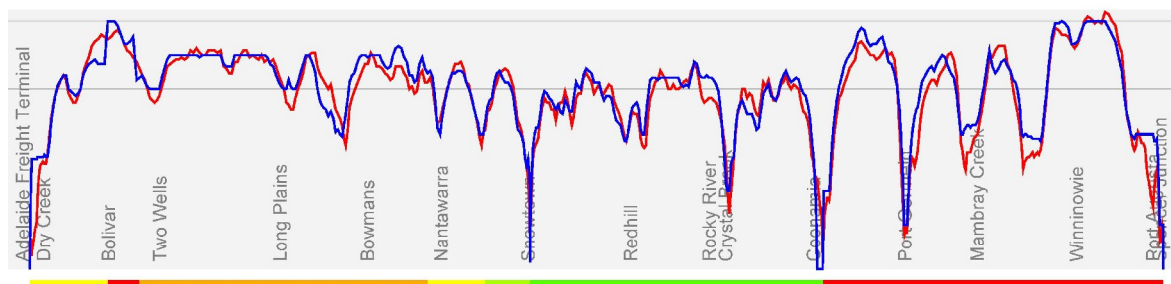


Figure 2: An example *Freightmiser* journey log.

The horizontal axis is distance, and the vertical axis is speed. The blue curve is the speed profile recommended by *Freightmiser*; the red curve is the actual speed of the train. The coloured bars below the graph indicate which of the seven *Freightmiser* speed profiles was selected. The selected profile was changed by the driver in response to information provided by the train controller on the required crossing times. After the first stop (Snowtown), the speed of the train was slowed (as indicated by the green bar) because an opposing train was running late for the next cross at Coonamia. After the second cross, the train was sped up to try to meet the scheduled time at the end of the journey.

The aim of *Freightmiser* is not to show drivers how to drive, but to provide them with information that will help them drive more efficiently. *Freightmiser* does not take into account signals or train-handling requirements. When it is not appropriate to follow the ideal speed profile, perhaps because of track conditions, restrictive speed signals or unexpected speed restrictions, the driver simply ignores the advice until it is appropriate to resume following the displayed speed profile.

2. DRIVING EFFICIENCY

The problem of finding the best way to drive to the next destination can be formulated as an optimal control problem. That is, we wish to find the sequence of control settings that will get the train to the next destination on time, and with minimal fuel consumption [2,3,4,5,6].

It is a matter of fundamental science that speed holding, where possible, consumes less energy than any other strategy. Conservation of energy requires the change in kinetic energy plus the change in potential energy to equal the work done by the locomotive minus the work done overcoming friction. In symbolic terms

$$\frac{1}{2}mv(b)^2 - \frac{1}{2}mv(a)^2 + [mgh(b) - mgh(a)] = \int_{x=a}^b [p(x)dt - q(x)dx] - \int_{x=a}^b mr(v)dx \quad (1)$$

where x is the position of the lead locomotive, m is the mass of the train, $v = v(x)$ is the speed of the train, g is the acceleration due to gravity, $h = h(x)$ is the height of the centre mass of the train, $t = t(x)$ is the time, $p = p(x)$ is the power applied by the locomotives, $q = q(x)$ is the total braking force and $r = r(v)$ is the frictional resistance. If the initial and final speeds are the same and if the cost $J(b) - J(a)$ of the strategy is the cost of power applied by the locomotives then

$$J(b) - J(a) = [mgh(b) - mgh(a)] + \int_{x=a}^b q(x)dx + \int_{x=a}^b mr(v)dx \quad (2)$$

If two different strategies move the train between the same two points then both strategies produce the same change in potential energy. The previous equation now shows us that the best strategy is the one that minimises the total of energy lost in braking plus the work done in overcoming friction. This occurs when variations in speed are minimized. Thus speedholding has an important role in an optimal strategy.

On flat track the most energy-efficient driving strategy is a *power-hold-coast-brake* strategy [2,3,4,5]. The driver applies maximum *power* to bring the train to the desired holding speed as soon as possible and then switches to *hold*. When the train comes close to the target location, the driver switches to *coast* and finally to *brake*. The hold speed depends on the time allowed for the journey and the speed at which braking begins is determined from the holding speed.

A section of track where the desired hold speed V cannot be maintained under maximum power is said to be *steep uphill at speed V* . In such circumstances energy consumption is reduced if the driver switches to maximum *power* before reaching the steep section and switches back to *hold* after leaving the steep section when the train returns to the desired speed. There is a unique optimal switching point. Similar remarks apply to sections of track where the speed increases above the desired holding speed V even when the train is coasting. These sections are said to be *steep downhill at speed V* . In such cases the driver should switch to *coast* before the steep section is reached and return to *hold* after leaving the steep section when the train returns to the desired speed. Once again there is a unique optimal switching point.

In order to find the optimal switching points when traversing a steep uphill section $[b, c]$ of track, we assume that the track is piecewise constant and describe a new local cost functional

$$L(v) = \int_{x=a}^d [\varphi(v) - L_v(v)]dt \quad (3)$$

where a is the position where the control must be changed to power, d is the position where speed holding must be resumed, $v = v(x)$ is the proposed speed profile and $t = t(x)$ is the elapsed time, $\varphi(v) = vr(v)$ is a special convex function defined in terms of the frictional resistance and

$$L_v(v) = \omega\{[t(d) - t(a)] - [t_v(d) - t_v(a)]\} + \left\{ \int_{x=a}^d r(v)dx - r(V)(d - a) \right\} \quad (4)$$

where $\omega = V^2 r'(V) + P$ is a special weight factor. Thus the optimal strategy finds a local balance between time taken and energy used for the power phase.

When steep sections of track are sufficiently close together, the control strategies for each of the individual steep sections may interact. For many routes, most of the optimal speed profile is in response to steep sections of track. The *Freightmiser* optimisation calculations take these into account [1,3,4,5]. The calculations also take into account speed limits and temporary speed restrictions [3,5,7]

Figure 3 shows four optimal speed profiles for a 55 km section of track. Each profile has a different holding speed and a corresponding journey time. The colour of the profile indicates the amount of power (green) or braking (red) used to follow the profile; grey is coasting.

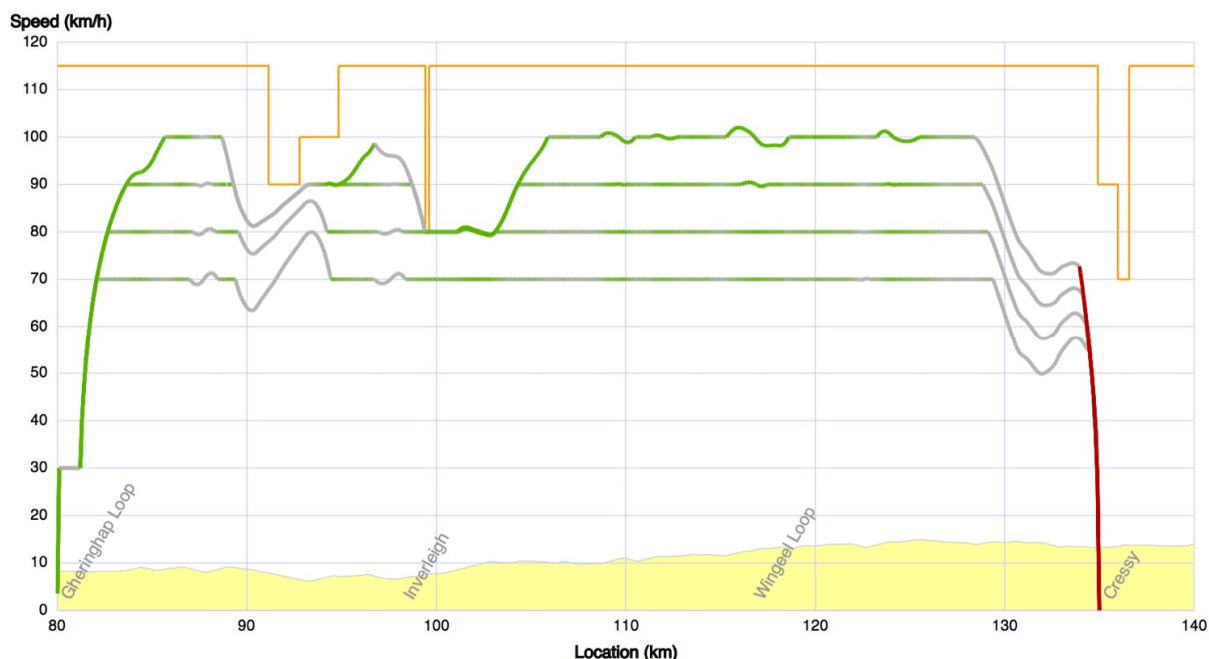


Figure 3: Optimal journey profiles

3. TRIAL RESULTS

The first *Freightmiser* trials were conducted in 2003 on revenue freight trains running on a 72 km section of undulating track between Goulburn and Moss Vale in New South Wales, Australia. A data logger was used to collect GPS data and time-in-notch data for ten trips without *Freightmiser* and five trips with *Freightmiser*. The trips with *Freightmiser* used 9-27% less fuel, with a mean saving of 15%. Journey times were not significantly different [8].

Further trials were conducted in 2004. Two locomotives were fitted with *Freightmiser* units, and used on services running on the 830 km journeys between Adelaide and Melbourne. Once again, performance with and without *Freightmiser* was measured using data loggers that recorded GPS data and time-in-notch data. When *Freightmiser* was used correctly, fuel savings were 5% through the steep Adelaide Hills, and 12% for the remainder of the route.

The most recent set of trials was conducted in 2007. For these trials, six portable *Freightmiser* units were given to selected drivers to use on their normally rostered services running on the 310 km route between Adelaide and Port Augusta, the 820 km route between Port Augusta and Cook, the 860 km route between Cook and Kalgoorlie, and the 490 km route between Port Augusta and Broken Hill. The trials included four different types of trains: 115 km/h passenger trains, 115 km/h freight trains, 110 km/h freight trains, and 80 km/h steel trains. The drivers were given minimal training—either one training run, or a short training session before their first trip. Of 84 trips with *Freightmiser* journey logs, the units were used correctly for 54 journeys. A common cause of non-compliance was that drivers left the *Freightmiser* on the default medium speed profile and then drove faster than the ideal speed profile to stay on time, rather than selecting a faster speed profile. Further training and greater familiarity with the technology would address this issue and improve compliance.

Mean fuel savings for compliant journeys varied from 3% for steel trains up to 14% for the high speed freight trains. As expected, there were no savings on passenger trains, since these trains have to be driven as fast as possible to meet the tight timetable.

Fuel savings on the low-speed freight trains was lower than on the high-speed freight trains because the low-speed trains are more constrained in how they can be driven. There is less scope for wasting fuel on these trains, and so less scope for saving fuel.

In general, increasing the power/weight ratio of a train will allow it to complete a journey in the same time with less fuel, but only if it is driven efficiently. Increasing the power/weight ratio of a train also allows it to be driven a lot less efficiently. There is greater scope for wasting fuel, and so *Freightmiser* is most effective on these trains.

Feedback from drivers was largely positive. Supervisors reported that *Freightmiser* would be an extremely useful aid to driver training, while experienced drivers felt that the *Freightmiser* display provided useful route data and confirmation of accepted energy-efficient driving principles.

4. CONCLUSION

Freightmiser is an in-cab system that provides information to help drivers save fuel and stay on time. Trials conducted between 2002 and 2007 have shown that fuel savings of up to 15% can be achieved.

Trains are an inherently efficient mode of land transport. But with dwindling oil supplies and the need to reduce CO₂ emissions, it is becoming increasingly important to maximise this efficiency. The savings in fuel costs and the reductions in CO₂ emissions that can be achieved with *Freightmiser* are significant.

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