ENERGY, TIME AND LONGITUDINAL TRAIN DYNAMICS COSTS USING ENERGY OPTIMISED DRIVING STRATEGIES IN HEAVY HAUL TRAINS

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Summary

There are many costs and overheads in operating a rail haulage service. Insights into how to reduce some of the operational costs can be obtained by focusing on costs that are affected by the driving strategy. Two main costs affected by the driving strategy relate to time and energy. There also exists a train dynamics cost which is influenced by longitudinal in-train forces. The cost optimisation of a heavy haul rail operation involves many factors such as train design, track design and scheduling. However an above-rail operator may only have control over the driving strategy and the train configuration with the other factors forming the operational limits.

This paper investigates the train dynamics cost, energy cost and time cost of a heavy haul train using an energy efficient driving strategy. In the view of the conference theme “Rail’s Digital Revolution”, comparison is also made with operational data to provide insights into and estimations of possible cost reductions in areas of energy, time and longitudinal train dynamics.

It was found that operational empty trains control strategies exhibit minimal energy and dynamics, but reducing journey times could reduce the total journey cost by 25%. Loaded journeys had higher possible cost reductions of up to 33%. To realise these cost reductions improvements to the track and rollingstock would be required to enable higher operational speeds that are required. Additionally the study found that longitudinal dynamic costs increased with faster journey times, but overall the longitudinal dynamics costs were low when compared to the time and energy costs. The study also found that energy-time efficient strategies generally produced good train handling, however some instances were found where non-energy efficient strategies produced better train handling.

1. INTRODUCTION

One way to reduce costs in railway operations is by changing the driving strategy of trains. Changes in the driving strategies will affect the journey times and costs such as energy, fatigue and wear. The Centre for Railway Engineering has been involved in train dynamics and energy research for over 20 years. This paper continues to explore the topic of longitudinal train dynamics and the effect of different train control strategies. With increasing computational speeds and increasing data these types of studies are now possible to reduce costs and improve safety.

Energy optimisation and scheduling optimisation are well-developed fields. Many tools exist to inform and assist operators in reducing energy and time costs. Energy efficient train control well understood and are presented in (1). However the optimisation of train dynamics is not as developed due to the high computational power required to generate the in-train longitudinal force data. It is generally recognised that energy efficient operation produces good train dynamics but there is limited detailed information on this. It is also noted that some modification of energy efficient driving strategies is required to minimise longitudinal in-train forces and the associated train dynamics cost.

Train scheduling has a large influence on the haulage cost, however this paper only focuses on driving strategy investigation and possible improvements in an unconstrained network. Findings from this study could be further coupled with scheduling investigations to find the optimal scheduling journey times. Also other optimisations involving train configurations, locomotive power and track design are other areas that can be investigated

The lowest energy costs would be achieved by control strategies that did not include any brake applications. However in normal operations brake applications are required to ensure operational speed limits are achieved. This study uses the opportunity of the simulation to investigate the effects of minimum energy control strategies where braking is not used. Hence some of the strategies produced would require improvements to track and rollingstock.

1.1 Energy Efficient Driving Strategies

Energy-time efficient driving strategies are well documented and those used in this study are based on a power-hold-coast-brake strategy. On flat level track an energy efficient speed profile would be similar to that shown in Figure 1.

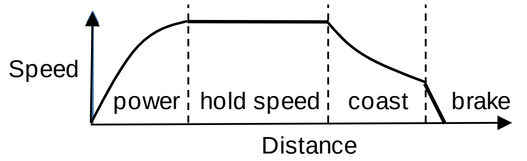

Figure 1: Energy-Time Efficient Strategy, Flat Track

As these strategies are only concerned with only time and energy, during the power and brake stages they use maximum power and maximum brake settings. As the end of the journey the coast point can be altered to find the most energy-time efficient strategy for a given hold speed, as shown in Figure 2. By varying the coast point, the brake point is also changed.

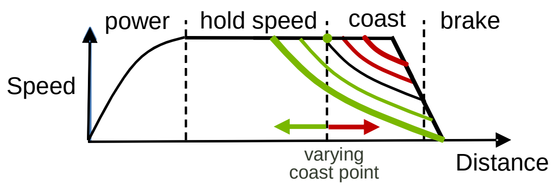

Figure 2: Varying the Coast Point

The most energy efficient strategies are based on achieving an average hold speed that is maintained by a locomotive throttle position of between 0 and 100% with no braking. However in normal operations to minimise capital costs train traction limits and track grades may not allow a speed profile similar to that shown in Figure 2.

When grades are encountered where the hold speed cannot be maintained the aim is to maintain the average hold speed over the section. An example of a steep grade is shown in Figure 3. To maintain the desired hold speed the train is required to have 100% throttle prior to the incline and until the hold speed is once obtained. The creation of minimum energy strategies require other similar variations, the full range of variations are well documented in (1). How these minimum energy-time control strategies affect the total cost of the haulage trip is a focus of this study.

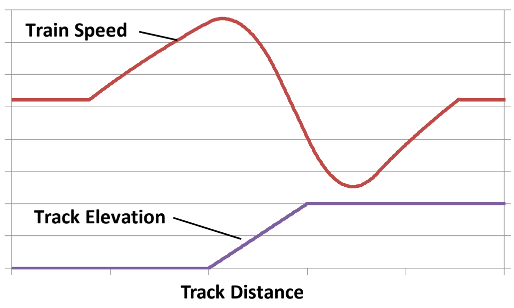

Figure 3: Energy-Time Efficient Example

1.2 Haulage Cost Function

To compare the different control strategies a cost function for heavy haul trains was used that was part of a previous study (2). The cost function used to calculate the journey cost for the experimental and energy-time efficient control is shown in the following Equation 1. The cost function includes costs that are affected by the train control strategy such as time, energy and train dynamic costs. The cost function does not represent the full cost of train operation that may include other costs such as operational overheads. The cost function is only an estimate to aid comparison of the strategies, more accurate cost functions could be developed by haulage operators by using more accurate in-house cost records.

Journey Cost =
C_t * time +
C_e * energy +
C_d + Cab * wagon braking energy +
C_{lw} * (loco tractive and dynamic braking effort) +
C_{cf} +
C_{cfw} +
C_{wfw} **Equation. 1**

where:

C_t (time cost) = $3940/hour
C_e (diesel energy cost) = $470/MWhr
C_d = Train Journey Derailment Cost Calculation
C_{ab} (air brake cost) = $0.04/kWh
C_{lw} (locomotive wheel wear cost) = $0.007/kWh
C_{cf} = Coupler failure cost calculation
C_{cfw} = Coupler fatigue and wear cost calculation
C_{wfw} = Wagon body fatigue and wear cost calculation

2. Example Haulage Operation

To investigate the effects of energy efficient control strategies on heavy haul operations an example haulage operation was considered. The route and train configuration was chosen as some experimental data for past operations was available and the associated train models had been previously validated (3).

2.1 Haulage Route

The haulage route used as an example for the study is located in Central Queensland. It is primarily used to transport coal from the Blackwater area to the port of Gladstone which is a distance of ~260km, Figure 4.

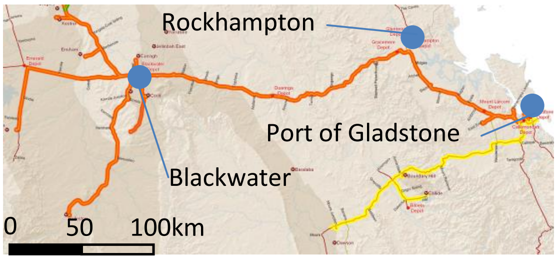

Figure 4: Blackwater Coal Line

In order to compare different track types a short section of ~110km was used as well as a 265km longer track section. The short track sections had minimal elevation increases of less than 20 metres. The longer track sections had an elevation increase of approximately 160 metres. Figure 5 shows the track elevation in the direction of travel for empty trains from the port towards the mines.

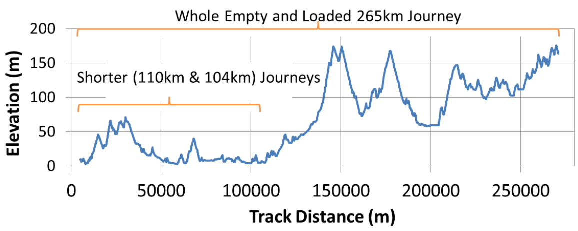

Figure 5: Track Elevation Details

2.2 Train Configuration

The train configuration used in the study was a coal train and consisted of three locomotives and 86 wagons. The locomotives were EMD GT42CU AC diesel locomotives with two at the head of the train and one mid train. The wagons were 20.6 tonnes empty and 106 tonnes loaded.

2.3 Cost Determination

The costs determined and presented in this paper are only those costs that are affected by the driving strategy for the route and use the previously mentioned cost function. The costs shown do not represent the total cost of the haulage operations but are only used to compare differences in the driving strategies

The study used the Centre for Railway Engineering Longitudinal Train Simulator (CRELTS) developed at CQUniversity to simulate the in-train forces and dynamics for the various driving strategies. Various past publications have detailed CRELTS and its validation, such as in (4). CRELTS provided the in-train forces and dynamics from which the costs results were calculated. The costs included, time, energy and fatigue costs, and are only approximations to allow for comparisons and discussion of the study.

3. RESULTS AND DISCUSSION

The various relationships gained from the results of the study are presented to provide some general insights on possible improvements in reducing costs of haulage operations. The benefit of simulation is that many scenarios can be tested. Some of the simulations are beyond operational limits and should be viewed only as theoretical possibilities. Some experimental data is presented alongside the simulation results to provide some comparison. While the sample size of the experimental data is small, it does provide some reference in regards to the nominal operational levels.

3.1 Energy-Time Relationships

The journey time ranges presented includes very fast journeys that would not be possible on the haulage system but very fast journeys have been included to show the relationships when extended beyond the normal operating conditions.

3.1.1 Short journeys

The energy-time relationships for the shorter (110km and 104km) journeys are shown in Figure 6. The theoretical energies (plotted as dotted lines) show the absolute minimum energy that would be possible on track without any intermediate gradient changes and assume a constant speed is achievable for the entire journey. The theoretical energies do include rolling resistance and curve resistances so lower energies would be possible with improvement in curve straightening and rollingstock rolling resistance reductions.

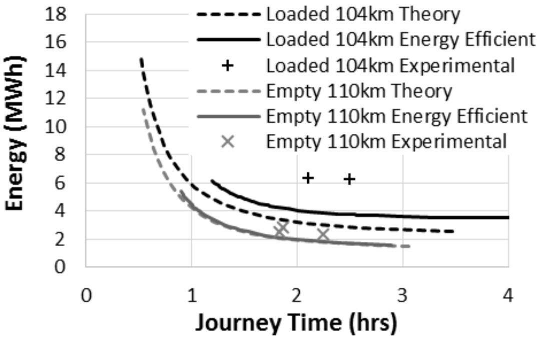

Figure 6: Energy-Time Relationship (Short Journey)

The energy efficient traces show the energies of the most energy-time efficient speed profiles for the current haulage system. These were determined using the energy-time efficient theories discussed earlier. For interest of exploring the topic of the study, the current speed limits of the track are ignored thus allowing the train to travel at the most efficient speed. The effects of higher speeds will be later discussed when presenting the total cost relationships which consider the dynamic costs along with the energy and time costs.

For interest, the experimental data is also plotted in Figure 6, indicating typical journey times and energy costs for the short track section. The experimental empty data is close to the most energy efficient profiles due to the limited amount of brake applications used in these experimental journeys. Conversely, the experimental loaded journeys use more brake applications and so exhibit higher energy than the energy efficient profiles. The loaded journeys display the largest possible energy reduction when compared to the empty journeys.

The energy efficient energies are slightly higher than the theoretical energies, as the speeds can not be maintained at a constant but vary due to the grades. These are also affected by ensuring the train speed is above a set minimum or stall speed. Figure 7 and Figure 8 show representative speed profiles for the empty and loaded short journeys, these are at a similar journey time of 2hrs to the experimental data.

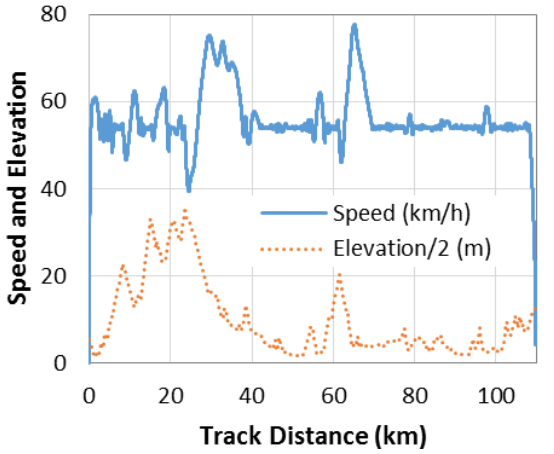

Figure 7: Energy Efficient Profile – 110km Empty 2hrs

The empty train speed profile shown in Figure 7 shows the action of the energy efficient strategy in that the speed is allowed to reduce just prior to steep declines and then is allowed to increase down the following decline. This can be seen most clearly around the 25km and 61km points. The empty train had enough power to maintain the hold speed on the inclines so an increase in speed before the inclines was not needed.

The loaded journey in Figure 8 had much lower minimum speeds and larger speed fluctuations to obtain the most energy-time efficient control. In the loaded case some speed increases before steep grades are required, an example of this can be seen at the 37km to 39km track position. The speed subsequently reduces as the train travels up the steep incline to a minimum at the point at 41km where the train crests the hill. The speed then increases as the train descends the steep negative grade. Without braking, speeds over the general track limit of 80km/h occur. This indicates changes in the track and train would be needed to obtain the most energy-time efficient operation for a journey time of 2hours.

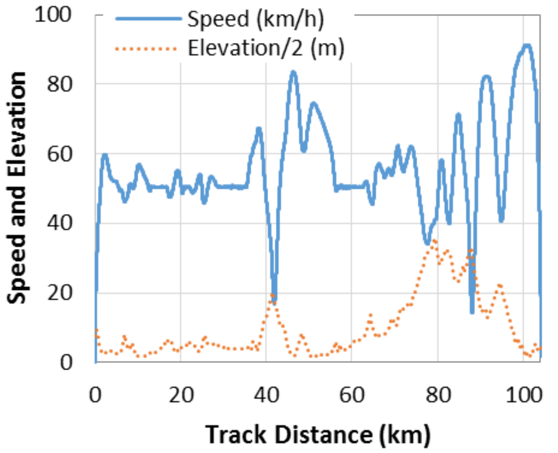

Figure 8: Energy Efficient Profile – 104km Loaded 2hrs

3.1.2 Long journeys

The long journey energy-time relationships are presented in Figure 9. Again the theoretical values includes some very fast journey times when compared to the typical journey times of the experimental values. Similar to the short journey results, the empty theoretical minimum energies and the energy efficient energies align closely.

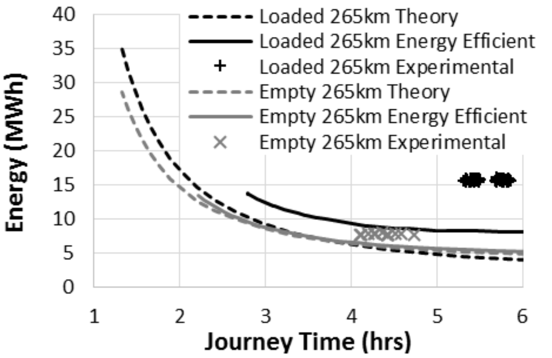

Figure 9: Energy-Time Relationship (Long Journey)

The loaded theoretical energy results, at times fall below the empty results which seems counter intuitive. However, referring to the track elevation in Figure 5, the empty journey starts at 0km and finishes at 265km with an increase in elevation of about 160m. On the return loaded journey from 265km to 0km the train descends 160m. This difference in elevation change greatly reduces the energy required for the loaded journey.

The loaded energy efficient results are approximately 4MWh greater than the theoretical minimums. This is due to the long steep grades present between 130km and 220km which create large potential energy changes. The locomotive power is such that the loaded trains speed significantly reduces on the upwards grades and increases in speed on the downwards grades, Figure 11. This effect is also apparent in the shorter journey results in Figure 6. The empty train results are more immune from this effect due to the lighter train mass. With improvements in either locomotive power or track grade reductions the energy efficient energies could be reduced towards the theoretical values. Similar to the short journey results, the loaded experimental results indicate the greatest possible reduction in energy and time occurs in the loaded journeys.

Figure 10 and Figure 11 show the energy efficient speed profile for a 5hr loaded journey and 4hr empty journey. Both profiles exceed the maximum speed of the line due to long and steep negative grades. To reduce speeds below the maximum limits brake applications would need to be employed during the journeys. However, the brake applications would increase the journey times and alter the minimum energies possible. As noted with the shorter journeys, changes to either the track or train would be needed to safely obtain the energy efficient results.

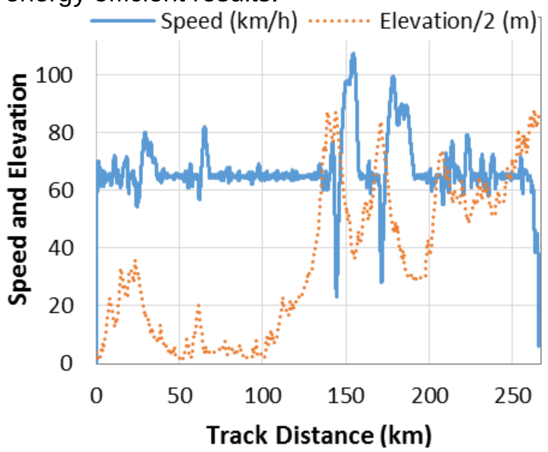

Figure 10: Energy Efficient Profile – 265km Empty 4hrs

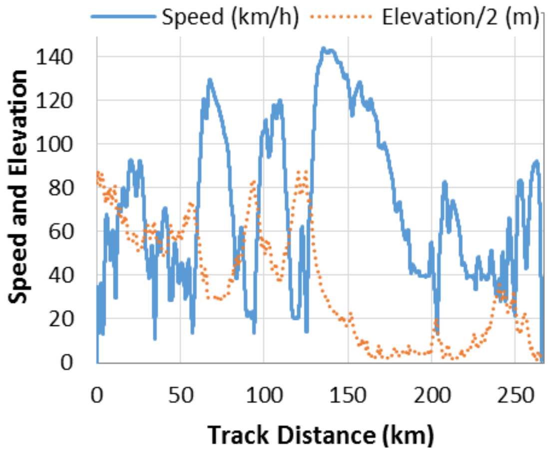

Figure 11: Energy Efficient Profile - 265km Loaded 5hrs

3.1.3 Energy-time cost relationships

Using the energy and time cost rates in Equation 1 the combined energy and time cost of the journeys were calculated and presented in Figure 12 and Figure 13. Both of these figures show that a reduction in time generally produces a reduction in cost. For very short journey times the cost does increase due to the larger energy cost increase outweighing the reduction in time cost. This is consistent with the study of (2) which concluded the time cost was a larger factor than the energy cost. If the energy cost rate increased, the minimum cost points in Figure 12 and Figure 13 would have higher journey times and move to the right.

Similar to the comments mentioned in the previous time-energy relationships section, the greatest possible reductions in cost occur for the loaded journeys. However, both empty and loaded journeys have the possibility of cost reductions if the journey time is reduced.

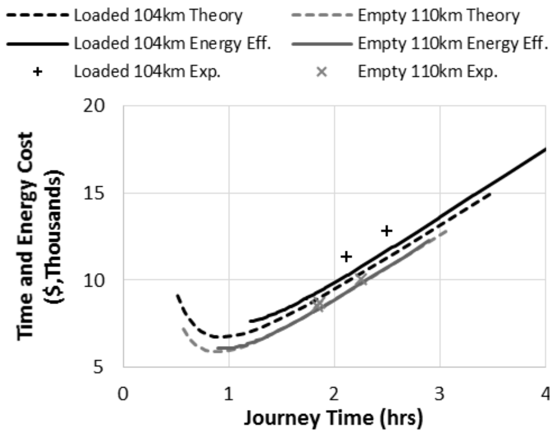

Figure 12: Energy-Time Cost (Short Journey)

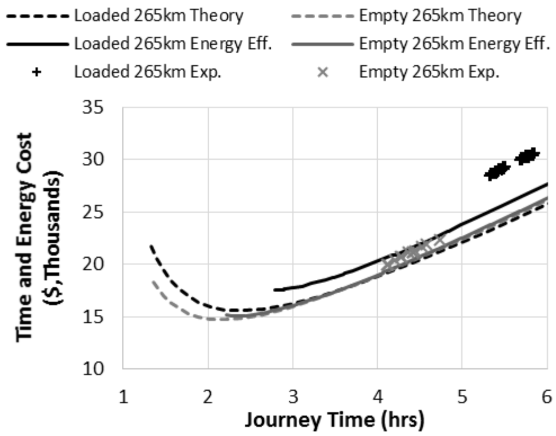

Figure 13: Energy-Time Cost (Long Journey)

3.2 Total Cost Relationships

The total costs were determined from the cost function of Equation 1 and previously documented in (2). The total cost function included time, energy, fatigue, wear and safety elements.

3.2.1 Total costs including overturning

The total costs for the short journeys are presented in Figure 14 and Figure 15. The Energy efficient journey costs are shown for a range of journey times along with the experimental data values. The energy efficient control exhibits a slightly lower total cost than the experimental data, which is expected due to the lower energy-time costs results displayed earlier.

In Figure 14, the loaded energy efficient journey for a time of 1.5hours has a large increase in cost. This is due to a high derailment cost element in Equation 1 caused by increases in the likelihood of the wagons overturning. Overturning is more probably because of the speeds in the energy efficient journeys are over the operation speed limits of the track. This highlights that to fully utilise faster journey times, the track and rollingstock would be required to upgraded to allow the higher speeds. The empty trains are not affected due to the lower centre of gravity of the empty wagons allowing higher speeds.

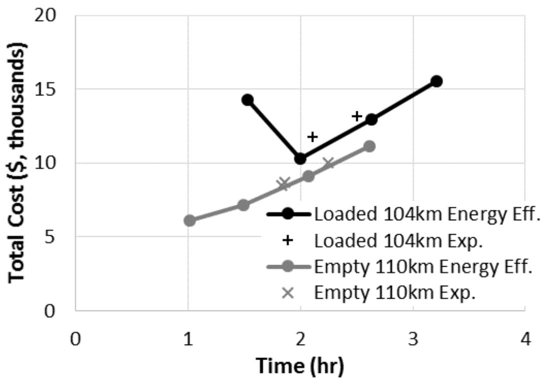

Figure 14: Total Cost (Short Journey)

The long journey total cost results (Figure 15) exhibit very large overturning costs for the empty trains with a time of 2.5 hours. The loaded journey energy efficient journeys where not shown as these contained very large overturning costs that masked any meaningful relationships.

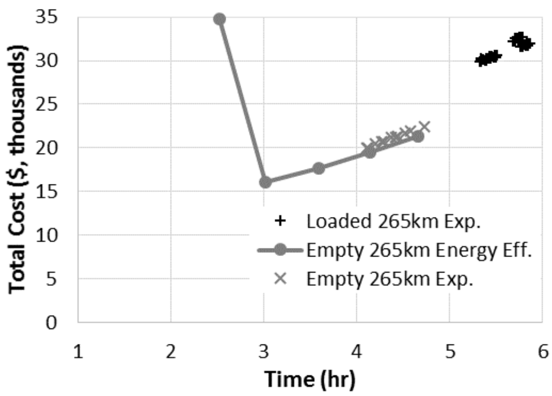

Figure 15: Total Cost (Long Journey)

Based on the total cost results it would be theoretically possible to reduce the total cost using energy efficient journeys for all journeys except the loaded long journey. However the speeds of the energy efficient journeys would need to be reviewed in light of the rollingstock and track geometry limits to ensure safe operation.

3.2.2 Total costs excluding overturning

In order to present the total possible savings, the overturning cost was removed from the cost function. This is based on the assumption that the track cant is upgraded to allow the energy efficient control speeds. The total costs excluding overturning are presented in Figure 16 and Figure 17. These show total cost reduction of 25% for empty journeys and 33% for loaded journeys would be possible, but only with significant upgrades to allow for the higher speeds of the energy efficient journeys.

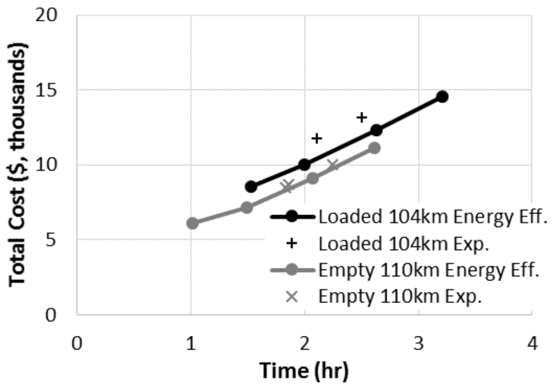

Figure 16: Total Cost Excl. Overturn (Short Journey)

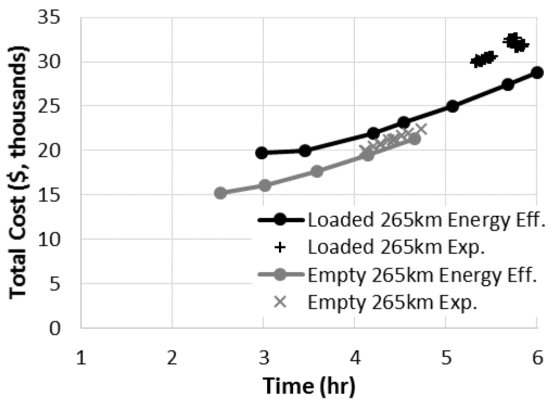

Figure 17: Total Cost Excl. Overturn (Long Journey)

3.2.3 Longitudinal dynamic costs

To view the longitudinal dynamic cost relationships, the longitudinal dynamic costs are displayed against journey time in Figure 18 and Figure 19. The empty journeys have very low dynamic costs compared to the loaded journeys, this is expected due to the lower longitudinal coupler forces that are typically encountered in empty trains.

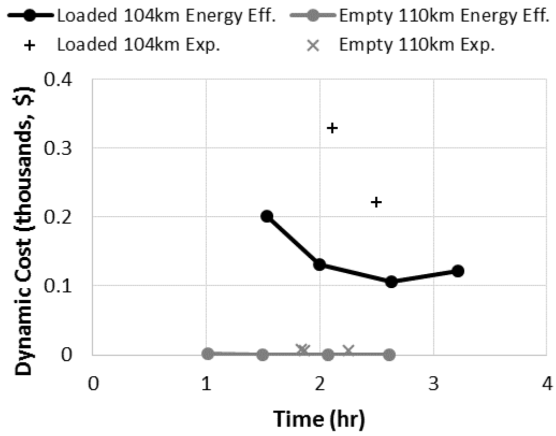

Figure 18: Longitudinal Dynamic Costs (Short Journey)

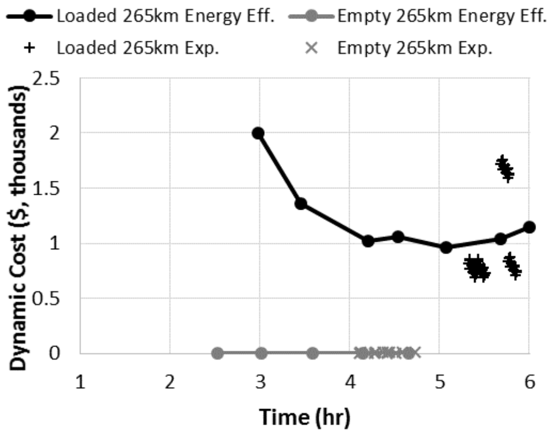

Figure 19: Longitudinal Dynamic Costs (Long Journey)

The loaded journeys data in Figure 18 and Figure 19 show that for the energy efficient journeys the dynamic costs are typically equal or lower than that of the experimental data. This supports the idea that energy efficient journeys do provide good train handling. For the long journey (Figure 19) some of the experimental data has lower dynamic costs than the energy efficient operation indicating that lower dynamic costs can be achieve by not following the energy efficient driving strategies. This is discussed further in the next Section 0.

The energy efficient data for both the short and long journeys show that the dynamics costs increase for faster journey times. But these cost increases are relatively small compared to the time cost savings shown earlier in the total cost graphs of Figure 16 and Figure 17. This indicates that faster energy efficient journey times can be more cost effective even with larger dynamic costs.

3.2.4 Dynamic costs against distance

The previous total dynamic costs for the experimental and energy efficient journey are similar, but to obtain a better understanding the dynamic cost data can be displayed against track section. Figure 20 compares the dynamic cost data for the loaded 265km-5hr energy efficient journey with the 265km experimental journey with the lowest dynamic cost. The figure shows there is some agreement in the locations of the cost peaks but the amplitude of the costs do vary. This highlights track locations where the energy efficient strategy is beneficial and track locations where an alternative control strategy would be best employed.

The peaks at 109km indicate that the experimental control strategy produces a smaller dynamic cost than the energy efficient control. The corresponding time series data for the energy efficient control at the track location is shown in Figure 21. This indicates the train is coasting with no throttle throughout the section. Up until 108km the front half of the train was descending and was pulling the rear over a hill. Around 108.2km the rear half of the train started to descend while the front of the train started to level out. This caused the rear of the train to compress the front, thus reversing the longitudinal coupler forces and causing the large compressive force at 108.4km.

In contrast, the experimental control time series data from 106km to 109km is shown in Figure 22. The experimental control slowly reduces the speed of the train with the dynamic brake as it travels over the crest of the hill and down the incline. This causes the front of the train to be in a compression prior to the rear of the train cresting the hill. This force state and the slower speed of the train eliminates the large compressive transient observed in the energy efficient control of Figure 21. This indicates that the energy efficient practise of coasting can produce worst train handling than if using brake applications to control the longitudinal dynamics of the train.

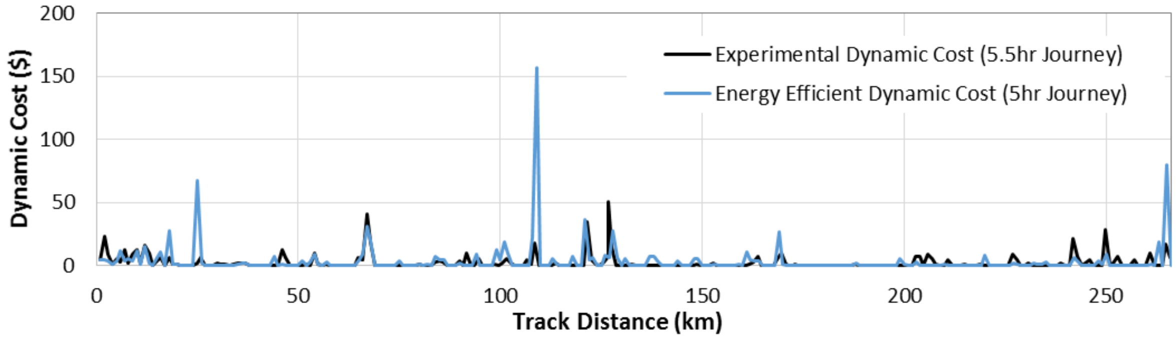

Figure 20: Dynamic Costs per Track Distance (Long Loaded Journey)

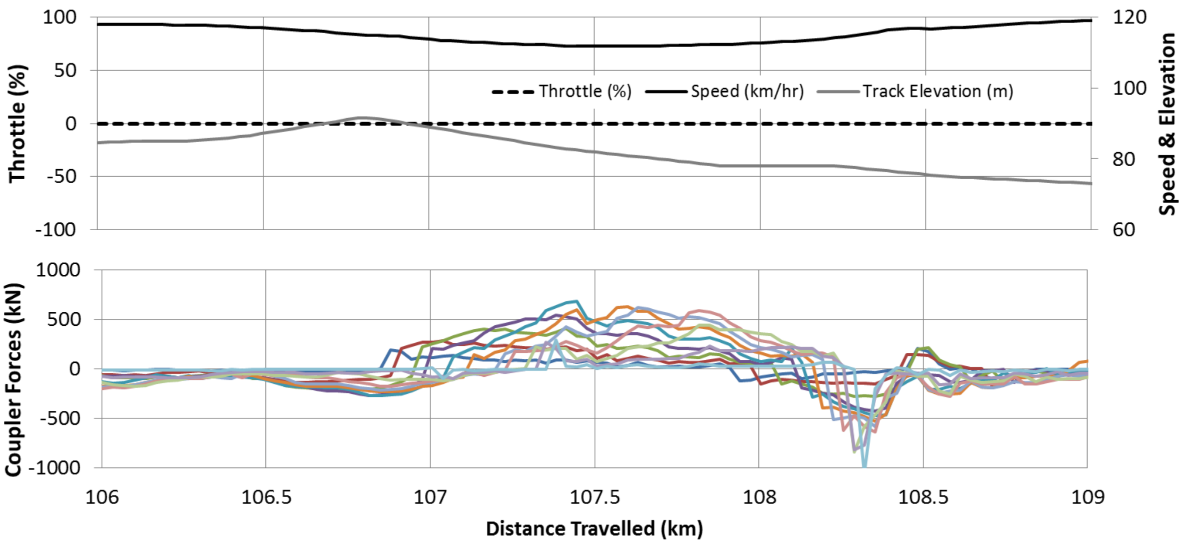

Figure 21: Energy Efficient Control – Loaded Train at 109km

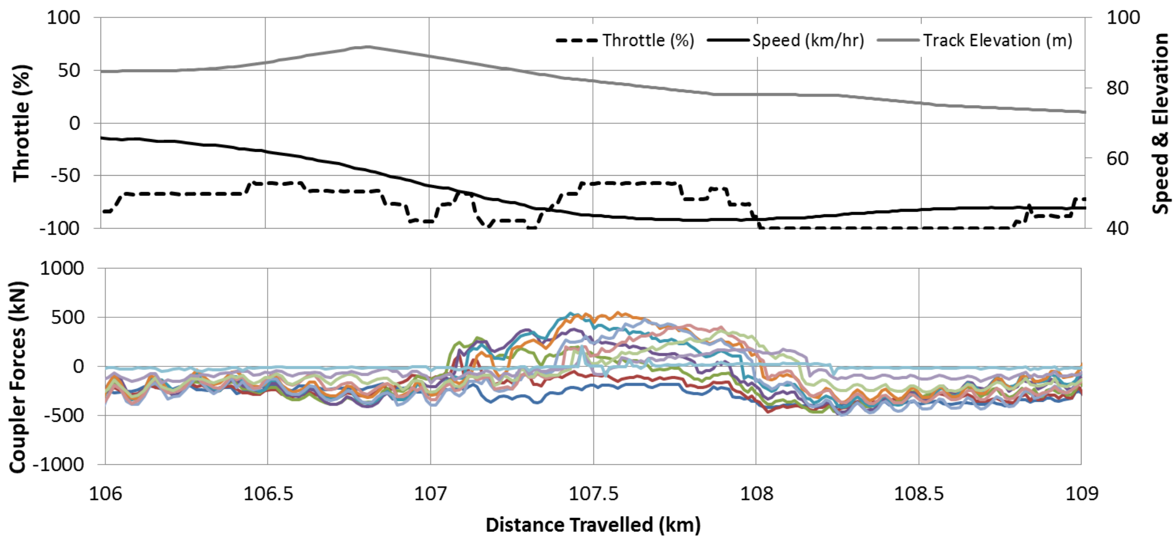

Figure 22: Experimental Control – Loaded Train at 109km

4. CONCLUSIONS

In general energy efficient train control was found to lower the total haulage cost for heavy haul trains in this study. However improvements in the track and rollingstock would be needed to allow the trains to travel at the higher speeds of the energy efficient control strategies. The largest cost reductions were produced by the energy efficient strategies resulting in faster journey times without significant increases to the energy and dynamic costs.

Energy efficient train control produced good train handling, but in some instances the use of brake applications can produce better train handling when negotiating changing grades.

In the study, the time costs determined were higher than the energy costs which indicated that it could be more cost effective to use energy-time efficient strategies that used brake applications. This would reduce the need for upgrades needed to operate the energy efficient control strategies at the higher than operational speeds required.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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