THE INTERRELATIONSHIPS BETWEEN TRAIN DESIGN, TRAIN HANDLING AND LONGITUDINAL TRACK LOADING

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ABSTRACT

Spoornet, South African Railways, developed advanced train handling techniques for its 200 car, 20800 tonne trains on the Ermelo-Richards Bay line. Originally intended to save energy and reduce train action forces, significant implications for track design and maintenance cost structures were discovered.

Rolling resistance and net elevation change define the minimum energy required to move a train. Any superfluous energy is dissipated in accelerated wheel and rail wear plus track damage due to longitudinal track movement. Advanced driving techniques apply traction and braking forces over shorter distances to minimize gross energy input into a train. Operating costs are reduced both by reducing the energy input and reducing maintenance resulting from excessive energy consumption.

Longitudinally applied locomotive/track forces are related to permissible coupler forces. Locomotive consist size is therefore a significant determinant of such forces. Advanced driving techniques contribute further to realisation of coupler strength potential, because dynamic train action is reduced and permissible quasi-static coupler forces are therefore higher. Longitudinal track forces may then attain critical values.

Locomotive fundamental tractive effort/speed and electric braking characteristics are therefore crucial to longitudinal track stresses. The latter may be increased at low speeds when insufficient power is supplied to a train. Energy is preferably imparted at the highest practical speed so as to operate locomotives at the lowest possible tractive effort.

Energy optimised driving techniques result in a wide band speed profile at many points on the line. This propensity is exacerbated by train length and poses a new problem for determination of superelevation under heavy axle loads

1. INTRODUCTION

Competition in transport markets, domestically between alternative modes and internationally between commodity suppliers, stimulates expansion of boundaries. In both heavy haul and general freight rail service, such competition tends to increase axle loadings, increase speed and increase train length. In the context of this paper, the prime consequence is escalating gross train tonnage. This is achieved by increasing the gross mass of individual cars and/or increasing the number of cars per train. Hence the aggregate tractive effort of individual locomotive consists tends also to increase. At the limit of permissible coupler strength, an increase in tractive effort may be beyond the capability of a single head end locomotive consist. Additional in-train locomotive consists may therefore occasionally be required.

Following commercialization, South African Transport Services has been succeeded by the Transnet company, of which Spoornet is the rail division. The principles discussed in this paper were developed in South Africa on Spoornet's Ermelo-Richards Bay line, as part of its train dynamics research and development program. The line conveys mainly coal over a distance of approximately 500km from the Transvaal coal fields to the Indian Ocean port of Richards Bay.

During upgrading of the Ermelo-Richards Bay line in the mid 1980's to carry 26 tonnes (28,7 short tons) per axle for cars and 28 tonnes (30,9 short tons) per axle for locomotives, the previous UIC-A rail was replaced by 60 kg/m (121 lb/yd) Cr-Mn rail. Two problems, which are thought to be interrelated, subsequently emerged. These are longitudinal failure of the track structure and abnormally high wheel/rail wear. They have been described respectively by Kuys (1989) and Venter (1989). Advanced train handling techniques were subsequently developed for the 200 car, 20800 tonne (22920 short tons) trains which have operated on this line since February 1989. Originally intended to save energy and reduce dynamic train action forces, significant train handling implications for locomotive/track interaction were also discovered. This paper discusses the linking relationship of train design and train handling to these two problems and the solutions thereto.

These discoveries are now being applied to all heavy tractive effort operations. The principles are applicable to both wheel/rail wear and track movement on high annual tonnage lines and the deleterious effects of high tractive forces on lightly constructed lines. Of course, heavy is a relative concept. A train of 4000 tonnes may be considered light, but if it operates over steep grades and needs a high tractive effort multiple unit locomotive consist, then it falls within the ambit of this paper.

2 ENERGY CONSUMPTION AND DISSIPATION IN TRAINS

2.1 Concepts of minimum and superfluous energy.

The minimum theoretical quantity of energy required to move a train from one point to another is defined by the total resistance to motion integrated over the distance travelled, plus or minus the net change in potential energy due to change in elevation. If the train is not stationary at either end of the distance, the net change in kinetic energy must also be included. Usually, actual energy consumption exceeds the minimum theoretical value by a significant margin. The reasons are predominantly false rise and fall and the efficiency with which the accompanying braking and train action are managed. Of course, reduction of resistance to motion, such as by lubrication of tangent track, may reduce total energy consumption. However, this avenue is not available for cars fitted with radial trucks, as on the Ermelo-Richards Bay line. The truth of this principle is confirmed by many successful railway programs to reduce energy consumption in recent years. As an example, energy consumption on the Ermelo-Richards Bay line was reduced by more than 40% during the period under consideration. That particular achievement was phenomenal, due to changing from independently driven head-end plus mid-train locomotive consists to head-end-only locomotive consists. It was also fortuitous, in that the saving was so large that it triggered further research into the phenomenon. Savings of 10-20% have been realized or reported in other instances, not necessarily incorporating the benefits of track lubrication. The existence of such phenomena therefore prompts the question of what previously happened to the superfluous energy which could be saved by improved train handling?

2.2 Dissipaters of superfluous energy.

Any superfluous energy consumed, over and above the theoretical minimum required to move the train, must ultimately be dissipated by degradation to a useless form. On the Ermelo-Richards Bay line the degradation took the form of severe longitudinal distress of the track structure, eventually becoming readily visible as in Figure 1. It was deduced that track structure must be able to dissipate vast amounts of energy before it becomes visibly distressed. In addition, accelerated rail wear on the high leg gauge face in curves was accompanied by a locomotive wheel flange wear rate some four to five times higher than normal. The condition of a worn flange is shown in Figure 2. Such energy degradation is insidious, because the effects are noticeable only after a protracted period of time, when the damage is well established.

Certain other lesser energy dissipaters are also discernible. Drawgears may dissipate energy due to train action. Unrefined train handling by individual drivers, such as power braking, inept handling through sags and poor anticipation, also dissipate superfluous energy. When non-radial trucks are employed without continuous rail lubrication, energy dissipation is also increased. In this case the wear may be less noticeable because it is spread over greater distances, including tangent track. Such dissipaters are classified as lesser by the rudimentary criterion that they do not cause abnormal damage. However, after refining practices to the full extent of conventional train handling, Spoornet found that there remained scope for significant further energy saving and that this further saving was accessible via an understanding of longitudinal locomotive/track interaction.

3 THE RELATIONSHIP BETWEEN COUPLER FORCES AND TRACK FORCES

3.1 Permissible coupler force.

Incessant demands for greater productivity and efficiency during the early 1980's drove Spoornet through a phase of ever increasing trailing loads hauled by ever increasing locomotive consist masses. During this period significant advances were also made in automatic wheelslip control, enabling usable adhesion to be increased from ±18% to ±24%. Multiple high adhesion locomotives also give steadier tractive effort, because there is less interruption due to wheelslip and manual correction. Total consist length could be 100 meters or more, averaging available adhesion over a greater length of track and masking isolated patches of relatively poor adhesion.

During this phase an awareness dawned that the utilization of potential coupler strength was unnecessarily low. Traditionally, a generous margin had been sacrificed to accommodate harsh train action. This practice was eventually challenged when planning the 200 car trains. Within the ultimate E/F-type coupler strength of 2000-2300kN (450-520 000lb force), maximum quasi-static coupler forces of 1000-1200kN (230-270 000lb force) were initially allowed. The quasi-static coupler force is defined as that force needed to drag a train up a long ascending grade without significant train action. Commissioning of a train dynamics instrumentation vehicle, described by Van der Meulen (1989), enabled a study of the relevant parameters. The insight so gained later led to development of advanced techniques to accurately predict and control train action. This enabled train drivers to contribute to fuller realisation of the coupler force potential. At that time quasi-static forces of 1500-1600kN (340-370 000lb force) were considered workable for E/F-type couplers, without increasing the risk of coupler failure beyond that which prevailed at the lower quasi-static coupler forces which were originally thought necessary. Advanced train handling techniques therefore more fully realize coupler strength potential, because dynamic train action is reduced and permissible quasi-static coupler forces are correspondingly increased. This is illustrated in Figure 3. Tractive efforts applied longitudinally to the track structure may consequently attain critical values beyond traditional peak values.

3.2 Self limiting tractive efforts.

Longitudinal forces applied to the track structure by locomotives are therefore related to permissible coupler forces. The aggregate tractive effort of a locomotive consist is frequently inherently self limiting, due to the ultimate coupler strength "safety valve". However, with heavy, high adhesion, expertly handled head end locomotive consists these forces may become critical. When in-train consists are employed, their total tractive effort is distributed between two couplers, front and rear. This effectively removes the coupler failure "safety valve" and allows extremely high longitudinal forces to be exerted on the track. Under such circumstances, Spoornet has measured forces of the order of 2000kN (450 000lb force), applied over the length of five locomotives. It is not known whether Spoornet's narrower track gauge of 1065┼ mm (3'-6") significantly reduces the resistance of the track structure to such forces, because the concrete ties are somewhat shorter than on standard 4'-8" gauge. Such forces are however large enough to cause distress.

3.3 Occurrence of rail breaks and kick-outs.

The author has collected data on recent rail break and kick-out occurrences on Spoornet tracks. They have been related to the position of crests and sags. Generally, rail breaks occur near a crest and kick-outs occur near a valley, as shown in Figure 4. When repairing a rail break, it is necessary to join in a piece of rail. When repairing a kick-out, it is necessary to remove a piece of rail. These observations suggest that rail breaks and kick-outs are influenced by applied longitudinal track forces, because they are always in the same direction, independent of direction of movement and independent of traction or dynamic braking. The movement of the rail is always away from a crest towards a sag, in response to gravity. Application of the principles discussed in this paper suggests that rail breaks and kickouts can be minimized by energy saving driving techniques.

4 TRACTION/BRAKING INFLUENCE ON TRACK FORCES

4.1 Locomotives dominate.

Many of Spoornet's operations, including all heavy haul operations, use self-steering or radial trucks. These minimize resistance to motion by avoiding flange contact. This means that heavy, concentrated force inputs from locomotive consists tend to dominate the issues under discussion. Locomotive tractive effort/speed and dynamic braking/speed fundamental characteristics are therefore crucial to longitudinal track loading. As the tonnage leader in electrically hauled trains, Spoornet has also uncovered some issues which are unique to electric heavy haul operations.

4.2 Tractive effort/speed characteristics.

All locomotives have a fundamentally hyperbolic tractive effort/speed curve. Consequently, very high tractive efforts may be exerted at low speeds. Achievable tractive effort is ultimately limited by incipient wheelslip. Skilled locomotive drivers anticipate wheelslip and pre-emptively apply sand. The passage of relatively few wheels, even just the lead truck of a locomotive consist, can significantly clean the running surface of a rail. Perversely, when high adhesion is required for traction it is frequently not available, but when low adhesion is required to limit tractive effort, it is frequently higher than desirable. Thus adhesion of 30-35% can be encountered under favorable conditions, such as under the trailing locomotives of a lead consist, or under all locomotives of an in-train consist. This may allow exertion of extremely high tractive efforts, which situation may be aggravated at low speeds when insufficient power is supplied to a locomotive consist. Ideally, the higher speed lower tractive effort portion of the characteristic curve should be used to impart energy to a train.

4.3 Influence of power source adequacy/inadequacy.

The balancing speed of a diesel-electric locomotive consist on ascending grades is essentially independent of the number of locomotives in the consist. Because the prime mover is on the locomotive, the ratio of available power to tractive effort remains constant, irrespective of the number of locomotives in the consist. The load can therefore always be designed to balance at full power. However, in the case of pure electric traction, installed substation capacity and voltage drop in the catenary mean that the power supply available to locomotive consists is not independent of the number of locomotives in the consist. The situation becomes critical when attempting to load the overhead supply beyond its design rating. If drivers are forced to reduce demand, to avoid tripping substations on over current or tripping locomotives on low voltage, then the locomotives operate on a reduced power curve. The consequently reduced speed means that locomotives enter the higher tractive effort portions of their characteristic envelope, which would normally be inaccessible due to balancing at full power. This problem is aggravated when equal load sharing between multiple consists is disturbed by the lead driver reducing tractive effort for fear of coupler failure at low speed and the in-train driver taking more than his share because his risk of coupler failure is much smaller. Despite steadily increasing coupler forces, no noticeable adverse locomotive wheel flange wear was encountered until the line was rerailed with Cr-Mn rail in the mid 1980's. However, abnormal wear was observed after introduction of the harder rail. It was then realized that the tendency of a non self-steering locomotive truck to increase its angle of attack under traction, was being aggravated by abnormally high tractive efforts. The adequacy or otherwise of the power supply is therefore an important determinant of the magnitude and consequences of longitudinal locomotive/track forces. Spoornet's experience is confined to separate drivers for each consist and radio remote control has not yet been used. It is however not expected that radio remote control would change a driver's perception of the risk of coupler failure in this situation.

4.4 Dynamic braking characteristics.

Heavy trains require powerful dynamic braking to facilitate fluent train handling. On track featuring movable frogs and continuous welded rail, using cars with self-steering trucks, the traditional limitations on high dynamic brake forces recede. When there is no risk of overturning the rail or wheels entering gaps in it, higher compressive forces are acceptable. The power output of an electric locomotive and hence also its dynamic brake rating, tends to be higher than when the prime mover is a diesel engine. When electric braking is used to dissipate energy at constant speed on long descending grades, as distinct from braking reliably to stop at the end of a movement authority, relatively high adhesion is acceptable. With creep control this may be even higher, and values between 22-25% could be considered. Under such conditions Spoornet applies dynamic braking forces of ±1450 kN (330 000lb force) to the rail. Increasing speeds on descending grades increases average speed almost for free, provided car wheel thermal limits are respected.

By transferring over-thermal-limit braking from car wheels to dynamic braking, the braking force tends to concentrate on shorter lengths of track and therefore applies significantly higher longitudinal forces at any given point on a descending grade. There is thus relatively little difference between normal tractive and braking forces, so that the locomotives of a heavy train exert high longitudinal forces on both ascending and descending grades.

5 TRAIN HANDLING DEVELOPMENT

5.1 New style train handling.

Spoornet's advanced train handling comprises two complementary aspects of locomotive/track interaction. One reduces both the magnitude of longitudinal forces as well as the extent or distance over which they are applied. The other reduces the absolute quantity of energy consumed by the system. It will in due course become apparent that these two are closely related, but separating the concepts facilitates explanation. The descriptions "energy saving" and "advanced" are both applied to particular driving techniques by Spoornet. Energy saving techniques are universally applicable, whilst advanced techniques add enhancements to handle super heavy trains. The techniques are fully compatible; therefore energy saving driving techniques are a subset of advanced driving techniques.

5.2 Limit energy consumption.

One way to reduce track damage is to reduce the amount of energy consumed by a train. Minimizing the energy input into a train minimizes the superfluous energy which can subsequently be wastefully dissipated. Two options are available. Firstly, the situation can be structured so that energy consumption is inherently low. Increasing train length enables potential energy to be transferred internally within the train by means of coupler forces, thereby reducing external energy requirements as shown in Figure 5. Coupler strength and management of train action ultimately limit the potential of this technique. In heavy haul service, it is also advantageous to interrelate brake ratio, signal spacing and quasi-static coupler loading such that power braking is not normally workable. Secondly, train drivers can be taught to consume energy frugally and to conserve that which they have already imparted to a train. Spoornet train drivers are taught to conceive the use of the throttle or accelerating lever as imparting a quantum of energy to a train with the intent of applying it to attain a specific topographical objective. Similarly, dynamic braking removes energy from the train, to be degraded to a useless form unless regenerative braking is available. Spoornet also teaches the concept of regarding the train itself as a temporary store for kinetic energy, to transfer energy from where it is not required to where it is required. It has been found that, at advanced level, drivers are receptive to these concepts. Also proving that there is nothing new under the sun, old hands recall similarities to steam locomotive train handling, where energy was consumed carefully because it had to be manually shovelled into the firebox.

5.3 Apply traction and braking forces over shorter distances.

Energy saving train handling generally applies traction and braking forces over shorter distances. Drivers are taught to equate energy to force times distance. Maximum quasi-static tractive and braking forces are essentially independent of driving technique, but energy saving driving techniques reduce the distances over which these forces are applied. Traction forces are also generally lower because locomotives operate at generally higher speeds. It is desirable to transfer as much kinetic and potential energy as possible from a descending grade to the next ascending grade, by application of elementary physics. These conditions minimize the absolute value of energy transferred from train to track because there is less superfluous energy to be dissipated. From a track point of view, both the forces and amount of energy which tend to move the track downgrade are reduced.

5.5 Impart energy at higher speeds.

Energy should preferably be imparted at the highest practical speed, so as to operate locomotives at the lowest practical tractive efforts. This technique reduces forces applied to the track, and sometimes allows tractive effort to be deliberately reduced at low speeds. This imparts energy at one location, for transfer within the train for use at some other point on the line.

5.5 Control of train action.

By happy coincidence, the techniques which minimize energy consumption also minimize slack action. However, because potential and kinetic energy are stored or transferred within the train itself, both simple and complex grade changes are typically negotiated with a large speed variation over the length of the train. Two techniques are employed to manage slack action. On simple grade changes, the cue for smooth transition from dynamic braking to traction is provided by the direction of speed change. On complex grade changes dynamic braking is useful to keep slack bunched. Both ensure minimal slack action. Practical application of these principles is facilitated by making drivers aware that they should not try to maintain a constant speed against nature where this is not essential to good train handling practice. They are taught that gravity should not be resisted more than is absolutely necessary, as this leads to application of traction and braking forces over longer distances and dissipation of superfluous energy. This in turn leads to increased track disturbance and accelerated wheel/rail wear.

5.6 Vehicle stability.

The use of cars fitted with stable trucks is material to the energy saving philosophy propounded in this paper. When a truck becomes unstable, lateral forces may attain unacceptable values before train speed is high enough to transfer significant amounts of energy across a sag. Instability also increases the track maintenance cost and may reduce or nullify any energy cost saving, or may even preclude it altogether. If a truck is stable up to any speed within the spectrum of feasible train handling, the transfer of energy across a sag may be optimised because there is only saving, with no trade-off against possibly increased maintenance. It is also important to acknowledge that drivers occasionally exceed maximum authorized speeds, when considering stability in relation to energy saving. Spoornet ensures high stability by using radial trucks. If conventional trucks are used, the issue of running stability must be raised.

6 INTERACTION BETWEEN TRAIN SPEED AND SUPERELEVATION

6.1 Wide band train speed profile.

Traditional freight train handling endeavors to minimize speed variation over grade changes to reduce or limit slack action. The underlying theory is that control of slack action will also control coupler forces. Spoornet's experience is that if train action is correctly understood, it is possible not only to control it, but to limit coupler force dynamic augment to extremely low values. By contrast, energy saving driving techniques widens speed variation over grade changes. Particularly through sags, where energy is transferred from one descending grade to the next ascending grade, the variation can be surprisingly large. Contrary to conventional wisdom, the dynamic coupler forces are very much reduced. The speed variation over a crest is less, because it is approached from an ascending grade on which speed is already limited by locomotive power or catenary capacity, and the speed on the next descending grade could be limited by the thermal capacity of the car wheels. Also, there is limited scope for reducing energy consumption over a crest because kinetic energy is proportional to speed squared and hence the potential wastage is inherently confined. Drivers are also loath to crest slower than locomotives permit, for fear of breaking a coupler at low speed/high tractive effort.

6.2 Influence of train length.

The range of speed variation at any given point on the track is a function of train length, because the latter effectively increases the time and distance over which such variation occurs. The longer a train, the more it couples together portions of train which would otherwise respond differently to grade or train handling inputs. One example is the head end of a train moving relatively slowly just before releasing brakes approaching the bottom of a sag, at which point on the track the rear of the train will be moving relatively fast. Conversely, when ascending a grade out of a sag the head end would be moving much faster than the rear end at any given point. Energy transfer by means of train length is thus accomplished at the expense of widening the speed range between front and rear of the train. Advanced train handling techniques therefore result in a wide band speed profile at many points on the line. This tendency is exacerbated by train length and may reach as much as 50km/h (30 mph) on trains of 2500 meters (8200 ft) length.

6.3 Superelevation and track maintenance.

In high axle load service it is desirable to specify superelevation so as to minimize track maintenance. However, when the train speed profile varies within a wide band, it is difficult to determine for what optimum speed curves should be superelevated. Spoornet is at present investigating techniques for ascertaining how to optimize the relationship and how drivers should handle their trains to minimize the speed band at any particular point on the line. The problem is compounded by the unscheduled but unavoidable speed deviations which must be superimposed on the natural or undisturbed speed profile of a train. Such unscheduled speed deviations arise from temporary speed restrictions for infrastructure maintenance, speed adjustment for maximum demand control, low voltage in the catenary due to bunching of trains, following a preceding train on caution signals and stopping while clearing a block section ahead. A positive advantage of energy saving driving techniques on a heavy haul line is that, because the speed profile is known, track maintenance may be minimized where speed is inherently low, to enable resources to be concentrated in those areas where speed is higher.

7 RECOMMENDATIONS

To implement the foregoing principles when optimising heavy haul services, as many as possible of the following items should be considered:

Avoid restricted speeds or hindrances in sags. These impede transfer of energy within trains and hence force application of higher tractive efforts later. Braking distances between signals and the placement of turnouts in positions where they would frequently be traversed at high speed are important. A study of train energy consumption in South Africa has drawn attention to the location of stations and crossing loops, many of which are located in sags. This is thought to be a relic of watering requirements for steam locomotives, because it reflects the propensity of water to gravitate to lower elevations. Rational design, unfettered by such extraneous requirements, suggests that stations or crossing loops should be located at crests, where train speed is naturally relatively low. This is subject to the requirements for picking up heavy trains from rest, which of course was not a requirement in the days of steam traction.

Train Drivers: Reduction of energy consumption entails higher average speeds and larger speed variations over grade changes. Such higher speeds must be used responsibly. Handling large speed variations without harsh train action demands highly skilled train drivers, otherwise unwanted side effects could negate the benefits. If design tractive efforts are high enough, power braking becomes awkward and this in itself encourages fluent, correct train handling over grade changes.

Pace trains: Manage train handling to minimize longitudinal forces by keeping trains moving at all times. This is one of the potential benefits of ATCS, because superfluous energy consumed must ultimately be dissipated in braking or higher maintenance.

Strengthen trains? Alternatives such as higher strength couplers and solid coupled trains have received serious attention. However, the provision of hardware which permits locomotive consists to apply significantly higher longitudinal forces to the track should be approached with care. The author is of the opinion that advanced train handling techniques using E/F-type couplers impose longitudinal forces near the limit which can be accommodated by state-of-the-art conventional track systems.

Increase dynamic brake rating. This applies to new locomotives and allows higher speeds through sags. Drivers then extend their planning horizon, in many cases from crest to crest without motoring in between. This enables forces between locomotive and track to be applied at relatively high speed, thereby minimizing use of the low speed, high tractive effort portion of the locomotives' characteristic curve. It also enables locomotives to be used more in the electric braking mode, where braking effort is deliberately limited, and less in the essentially unlimited traction mode. Spoornet uses heavy haul locomotives with dynamic brake ratings of 4500 kW (6000 HP) and is investigating acquisition of locomotives for general mainline freight service with dynamic brake ratings of 4000-4500 kW (5400-6000+ HP). This incidentally also permits full utilization of installed power electronics rating.

Widen curves. In new construction it is desirable to reduce sensitivity to superelevation. Whilst more compelling determinants of curve radius frequently exist, the potentially damaging effect of high longitudinal forces should be recognized. Alternatively, avoid tighter curves in areas where high speed variation is expected. These locations can be determined by computer simulation, but would typically be in sags.

8 CONCLUSION

It is concluded that train design and train handling techniques are a significant determinant of longitudinal track loading and hence of related operating costs. These costs may be significantly reduced both by limiting energy input and by reducing maintenance resulting from superfluous energy consumption. When due care has been exercised, the philosophy in this paper leads to a new style of train handling, which is easy on energy consumption, easy on track maintenance and easy on dynamic train action forces.

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**Published in Proceedings of the Workshop on Heavy Axle Loads,
Pueblo: International Heavy Haul Association, Association of American Railroads, U.S. Department of transportation and Federal Railroad Administration, October 1990, Pages 22-1 to 22-10**

Figure 1. Longitudinal distress of the track structure.

Figure 2. Severe locomotive wheel flange wear.

Figure 3. Full realisation of coupler strength potential.

Figure 4. Location of rail breaks and kick-outs.

Figure 5. Energy consumption as a function of train length.