

Towards the next level of train handling technology

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INTRODUCTION

The next level

As the Information Age evolves, it has become evident that completely solving time-honored problems, through application of information technology, frequently leads further than intended. Typically, the solution separates information content embedded in a bothersome design from equipment that physically does the work. Eliminating problems in this way also liberates resourceful people to move their business to the next level, by exploiting the full potential of access to previously implicit information. This paper examines some aspects of train- and braking technology in this context: Spoornet's heavy haul businesses provide the research setting. The purpose of this paper is to stimulate thought, and hopefully also action, in the field of informationalized train technology.

Spoornet's heavy haul operations

Spoornet operates two heavy haul businesses. COALink exports 75 million tons (1 ton = 2000 pounds) of coal per year over the Ermelo-Richards Bay line, on ruling grades in the loaded direction of 0.625% ascending and 1.52% descending. Orex exports 24 million tons of iron ore per year over the Sishen-Saldanha line, on ruling grades in the loaded direction of 0.4% ascending and 1% descending. On both lines, trailing loads of 200 cars gross 22,800 tons at the maximum axle load of 28.6 tons. Up to four 369,000 pound, 5200 rail horsepower, straight electric locomotives provide head-end-only power. Braking is by direct-release AAR-compliant or -compatible equipment. These businesses offered extensive scope for research and development in the field of this paper.

Spoornet's world record freight train

During the mid1980s, Spoornet upgraded its Ermelo-Richards Bay operation, over four years. During that period, it combined trains, to provide time slots for construction occupations. Those trains employed distributed power, operated by a crew on each locomotive consist using intra-train voice-radio communication. That experience gave insight into train dynamics under extreme conditions, and prompted questions regarding possible ultimate limits on train length and weight. Hence Spoornet's legal predecessor, South African Transport Services, probed the limits of conventional mechanical equipment and train handling knowledge, with a 660-car train of 78,000 tons all-up weight, in 1989. It is currently still the world record holder.

Insights gained

A major challenge was keeping the world record train in one piece over undulating terrain. Significant speed differences occurred within the train, compelling involuntary modulation of train speed to contain coupler forces. This experience suggested that development beyond currently accepted limits should take place within a paradigm of modulating power and braking, independently within various segments of a train. The objective is to maintain the same acceleration (or retardation) at each vehicle in a train. In this paper the word *vehicle* can mean *locomotive* or *car*.

Heavy haul operations stress longitudinal mechanical components more than other types of operation. Globally, Association of American Railroads influence on end loading, couplers and drawgear, and automatic braking, has informed the dominant technology. Alternative mechanical technologies do not seem to be commercially viable in the relatively small quantities involved in the heavy haul segment of the railroad industry. Instead, the trend is to extend competence boundaries by technologies that transcend constraints imposed by the dominant technology, employing information to optimize the relation between design intent and actual service.

SOME FUNDAMENTAL TRENDS

Technological limitations...

Air brake systems suffer from physical limitations regarding propagation speed and flow rate. Regarding propagation management, direct release brakes make use of features such as accelerated application and emergency application, whereas graduated release brakes make use of limited train length and a second trainpipe. Control of brake cylinder pressure build-up makes use of artifices such as inshot valves, rate-of-rise choking, differentiating between service and emergency applications, and manual *goods* or *passenger* selection. Some attributable problems are slack action, increased braking distance and operator stress. Respectfully, fixes contrived within the same physical limitations that first caused a problem, can be no more than palliatives. One can only eliminate them by moving to the next level, a higher performance order.

... versus market requirements

Because of the above-mentioned limitations, two train technology trends are emerging. On the one hand, industrial goods and merchandise freight (such as are still on rail) gravitate to relatively short, light trains. On the other hand, bulk commodity and wholesale intermodal freight gravitate to relatively long, heavy trains. In a broad global context, that admits several exceptions, the former have become associated with graduated release braking, whereas the latter have become associated with direct release braking. Perhaps influenced by that distinction, industrial goods and merchandise freight is relatively chaotic (indeterminate origin-destination pairs and quasi-spontaneous demand), whereas bulk commodity and wholesale intermodal freight is relatively orderly (limited origin-destination pairs and consolidated demand). The convergence of graduated release and chaotic characteristics will drive short, diverse, trains to

automation, as is already emerging in Europe. However, direct release braking at least, and probably also other aspects, for example train action, has thus far precluded serious contemplation of automating long, heavy freight trains.

Distributed power

Distributed power by radio remote control has developed over several decades. Its attractions are twofold. First, it reduces longitudinal forces through offering either synchronous or independent application of power and dynamic braking among two or more locomotive consists. Second, it assists charging and recharging of the automatic air brake system. Nevertheless, it can only alleviate weaknesses attributable to the physical limitations of relatively slow automatic air brake propagation and retarded brake cylinder pressure build-up. Furthermore, in a logical sense, control of distributed power may be a subset of continuous intra-train communication, but continuous intra-train communication is not a superset of distributed power. The latter argument equates the value of radio remote control of distributed power, to its value as a parallel element of a redundant system.

Intelligent training and driving

Traditional train handling wisdom is predicated on combining proactive behavior (based on knowledge of the equipment and terrain) with reactive behavior (based on observed feedback from the train). Train dynamics algorithms that have emerged in training aids such as simulators, and driving aids such as *LEADER* from New York Air Brake, admit two streams. The first reinforces the traditional approach. Regarding feedback, such aids imply the premise that there must be some form of train action that the locomotive engineer must handle. It reflects the direct release, and subsequent recharge, characteristics of the automatic air brake system, as well as the contingent dynamic behavior of drawgear. Realistically, these physical characteristics will probably be with the industry for many years to come. The second asks whether it is feasible to develop an alternative approach. It should not base train handling on observed phenomena, but rather seek to predict power and braking requirements in real time with sufficient accuracy to automate driving, without inducing undue longitudinal disturbances within a train. Location systems such as global positioning (GPS), inertial guidance, and lineside transponders, make it possible for these two streams to converge, in that it is feasible to know in real time both where a train is moving on a track profile, and what are the contingent dynamics. The final missing link is a philosophy within which to automate the driving function.

ECP braking and intra-train communication

Electronically controlled pneumatic (ECP) braking raises physical limitations by some six orders. Hence it effectively eliminates the propagation and build-up weaknesses inherent in automatic air brake systems. It also eliminates the dysfunctional effects that stem from uneven distribution of brake power, along a train. The concomitant separation, of system control and compressed air storage functions, may, depending on duty cycle,

also improve the state of charge of the brake system. This permits removal of length constraints on graduated release braking, thus opening the way to automated driving or control of long trains.

The bandwidth that is required to support conventional automatic air brake functionality is some 10 bits per second. The bandwidth that comes with ECP braking is several kilobits per second. The ability of ECP braking to communicate along the length of a train offers an alternative path that can support other functionality. This can, among other, potentially control more distributed power nodes at lower cost per node than can traditional radio remote control. It also stimulates many queries regarding additional functionality such as parallel redundancy and automation, which can enhance the performance and reliability of the whole-train system.

RESEARCH QUESTIONS

What is the industry heading?

New intra-train communication technology certainly addresses current air braking weaknesses attractively. Equally importantly, beyond that, new vistas in the field of train handling now seem worth examining. The following are some key issues that will underpin the new potential.

Consider first two variables that seem to underlie the trends described above, namely *Automatability* and *Smartness*. For the purpose of this paper, the authors propose the following definitions. Automatability is the degree of technological ability to support whatever automation a designer can conceive. It is *low* when feedback loops are incomplete, and *high* when feedback loops are closable. Smartness is the level at which

Table 1

Train control types		Smartness	
		Low	High
Automatability	High	Automatic train operation	Subject of this paper
	Low	Automatic train stop	Manual operation

integration, of the variables used to control a train / track system, takes place. It is *low* when integration is embedded at hardware level (such as dynamic / friction brake blending). It is *high* when integration occurs at information level, such as when a train with diverse vehicle

characteristics traverses a complex track profile. Cross-tabulating these two variables yields Table 1.

Definition of field

Consider the above four quadrants, one by one, starting with *automatic train stop*. It tolerates low Smartness among vehicles comprising a train. Both locomotives and

trailing stock embed braking functionality at hardware level, by means of a continuous automatic brake pipe. Low Automatability thus suffices to realize this quadrant. Its functionality is however, limited to stopping a train when its human operator exceeds authorized movement or speed. It is indifferent to train- or brake type, whether freight or passenger, direct release or graduated release.

Second, conventional *manual operation* demands high Smartness to perform substantial integration at information level. For this reason it is both vulnerable to human failings and difficult to model. Furthermore, Automatability is low, in an environment where, typically, feedback is incomplete and train / track interaction is complex. The majority of the world's freight railways therefore reside in this quadrant.

Third, automatic train operation demands high Automatability, but can tolerate low Smartness. In the city rail field, Automatability is high because the process logic of short trains, that one may consider a single unit, is deterministic, and feedback loops are complete. Low Smartness is sufficient to support propulsion and blended braking embedded at hardware level. The world's automated city rail systems, particularly the many that predate microprocessors, offer evidence that this type eminently fits them.

Fourth, the quadrant representing high Automatability *and* high Smartness, is the subject of the present research. In the freight train field, it has recently become possible to entertain queries regarding the extent to which automated operation is feasible. Possible responses cover a wide spectrum.

At the one end of the spectrum, there is appreciation of the essentially chaotic nature of industrial goods and merchandise freight traffic. Such demand-oriented traffic is characterized by randomness regarding vehicle type, length of haul, and train size, and hence amenable to automating the entire origin-to-destination process without traditional railroad interventions such as consolidation into trains, switching en route, and distribution at destination. Exploratory solutions are emerging in Germany [1], where rail automation in one way or another has become well established. For such trains, the whole essentially replicates the characteristics of a single vehicle (through individually powered vehicles, or locomotive plus a few cars). This approach is feasible because each vehicle can look after itself regarding braking only, integration taking place at hardware level. The presence of side buffers also eliminates questions concerning train action. These characteristics thus essentially replicate those for city rail, and in that sense the development fits the high Automatability, low Smartness quadrant.

At the other end of the spectrum, traffic in bulk commodities such as grain, coal and ore, lends itself to consolidation into long, heavy trains. The characteristics of such a train do not replicate the characteristics of a single vehicle. Locomotives are capable of powering and braking, but cars are capable of braking only. Traditional train handling wisdom is predicated on the presence of some slack between vehicles, as well as of sufficient train length and weight to cause coupler failure under some conditions. Locomotive engineers use high Smartness (of the human variety) to maximize their objective function at the information level. However, Automatability for over-the-road line-haul freight operations with direct release brakes is low. The coming of ECP

braking, with its graduated release feature, closes the feedback loop necessary for automatic control of braking, and thus elevates freight train automatability into the fourth quadrant. Let us now examine three areas that need development to make this quadrant active.

Segmented train control—a hypothesis

The authors hypothesize that, as train length increases, the number of significant grade changes under the train increases concurrently, and consequently situations arise in which it will be advantageous to distribute braking effort, not uniformly as is conventionally taken for granted, but discretely in various parts of the train. Operating distributed power in independent mode already approximates this condition, although the portion of train under the control of a particular locomotive consist is statically indeterminate except in steady-state conditions, such as on a long ascending grade. A segmented train would thus have power *and* braking applied according to the requirements of individual segments. Ideally, a segment would be a single car. In practice, many reasons may exist to segment a train into larger units. They may relate to physical configuration, such as married pairs or articulated rakes, or to information throughput limitations, such as bandwidth or processing power. The following three paragraphs strengthen the hypothesis.

Energy management

It is possible to transfer potential energy from a descending grade to a following ascending grade by minimizing use of braking, either dynamic or friction, and using kinetic energy as a transfer medium through the intervening sag. Spoornet has found that on long, heavy trains the consequent energy saving can be significant. However, the variation in train speed at specific locations on the ground can be large, making it difficult to maintain superelevation in curves at such locations. Two possible alternative techniques come to mind. One is to maintain speed relatively constant through a sag, that is small acceleration or retardation, and apply braking only on cars on the descending grade. The other is to use regenerative braking, to transfer potential energy from locomotives on descending grades to locomotives on ascending grades, through the catenary system. An electrified railroad, such as Spoornet, has the possibility of regenerating electric power into the supply system, as opposed to dissipating it in the resistance grids of a dynamic brake. With traditional control systems this was only possible into a direct current supply but with modern power electronics it becomes possible to regenerate into an alternating current supply. Segmented control of braking, through intra-train communication, would facilitate these alternative techniques.

Coupler force management

An automatic air brake application may increase draft forces to critical values when a long, heavy train passes over a crest. Uniform application of car brakes on the entire train, while its rear portion is still on an ascending grade, but the leading locomotive consist cannot provide sufficient dynamic braking to prevent run-out of slack,

risks a break-in-two. Furthermore, even slackless trains are subject to coupler strength limitations. Segmented control of car brakes through intra-train communication offers the potential to minimize both peak draft forces, wherever they occur in a train, and energy consumption of locomotive consists, toward the rear of the train.

Idealized functionality

Braking and power are identical, that is, longitudinal forces exerted on a train, except that they are of opposite sign. Existing reality for most freight train operations is discretely-distributed location (head-end and possible remote consists) and control (synchronous or independent) of power and dynamic braking, and continuously (but uniformly) distributed location and control of (automatic) car braking. Ideally, the objective function for control should optimize train handling to minimize the cost of delivering agreed service. The foregoing arguments suggest that segmented control of the available power and braking functionality will have value in achieving the objective. A power and braking blending algorithm, that modulates segmented power and braking, as a function of train position relative to terrain, will be necessary. Such a scheme exceeds the ability of most unaided human operators: This paper describes a search for an appropriate paradigm on which to base such an algorithm.

Motives for autopilot

The notion *autopilot*, as used above, is foreign to the freight railway industry, and therefore needs explanation. The authors believe that, as used in the aircraft industry, many people have at least a layperson's understanding thereof. In the present context, the authors mean what one could also call auto-driver or auto-engineer. The word pilot itself is not foreign to railway ears. It is distinct from navigation, and more than the automotive notion of cruise- or speed control. The latter is already available in the European railway environment, but is not suitable for handling heavy freight trains. Such trains will probably still have a human operator, but an autopilot function can add value by doing the job better. The authors use the word autopilot here for lack of a better term: Of course, a suitable name will emerge from common use when the time is right. The following are some of the reasons why one would consider a railroad autopilot.

First, how close can one work to prudent limits and still deliver reliable service? Spoornet, for example, found that it compromised mission reliability by working at high coupler forces. The closer one approaches real limits, the more sensitive the system becomes to human failings such as error and misjudgment. Automation offers a means to consistently work close to critical limits, without ever exceeding them.

Second, there exist relations among design specifications, actual loads, and maintenance environments. Each component, when working at its assumed capacity, will have certain maintenance requirements and a corresponding life expectancy. However, variability in equipment performance due to unintentional or surreptitious mismatch among design, use and maintenance, lowers output quality. Tighter control of loads applied to equipment, through automation, will enable operators to minimize assignable causes of variance, and so optimize the design-use-maintenance match.

Third, reality is such that training cannot cover all exigencies (such as infrequently occurring situations), and human nature has a propensity for taking the easy way out (such as not anticipating a problem, but waiting for it to surface). Consequently, incidents occur in which the ability or judgment of a human operator are subjected to scrutiny. Again, automation will reduce stress levels on locomotive engineers and facilitate reliable handling of unfamiliar situations. This vision also raises issues such as what to do with an existing pool of driving skills. Does one leverage existing talent to raise productivity, or de-skill jobs in the direction of automated driving?

Fourth, communications-based train control is stimulating convergence of several functionalities. The extent of movement authority together with all fixed and temporary speed restrictions (data in network system) may be downloaded to a train. The actually permissible speed is a function of train composition, state of maintenance, and position on track profile (data on board). At present the link between them is, at best, positive train separation, and at worst, a fallible human operator. Autopilot potentially provides a more comprehensive system integration solution. In an industry that is rapidly entering the Information Age, it is apposite to consider what knowledge one should locate on board the train, what knowledge one should locate in the control system, and what hierarchical relations should exist among them. The existence or imminence of autopilot capability informs such a decision.

TEST PROGRAM

Objective

Spoornet is at present investigating and evaluating technologies to loosen constraints and tighten control on its COALink business. The operation has reached a stage where incremental improvement seems less attractive than a paradigm shift that will reengineer processes, and renew or refurbish equipment. This is because the present system, as indeed any railroad system, embodies many discontinuities and non-linearities, and consequently changes to individual parameters are frequently less successful than expected. The package encompasses permissible axle load, train length and flexibility, locomotive upgrading, reliability of systems, subsystems and components, distributed power, and ECP braking. Current drawbar forces are high, of the order of 180 tons, under quasi-static conditions with measured peaks as high as 210 tons, leading to fatigue cracking of drawgear components and break-in-twos. Two-hundred car trains have long brake application and recharge times. Several technologies have now converged sufficiently that attractive scenarios are emerging. In particular, in the context of this paper, intra-train communication as an enabler of both distributed power and segmented braking is a potential major contribution to improved mission reliability at higher equipment loading levels. There thus existed a need to contemplate performance objectives for in-service evaluation. This section describes research conducted to explore realistic expectations and development targets for distributed power and segmented braking, within an ultimate vision of autopilot capability, when that becomes commercially available.

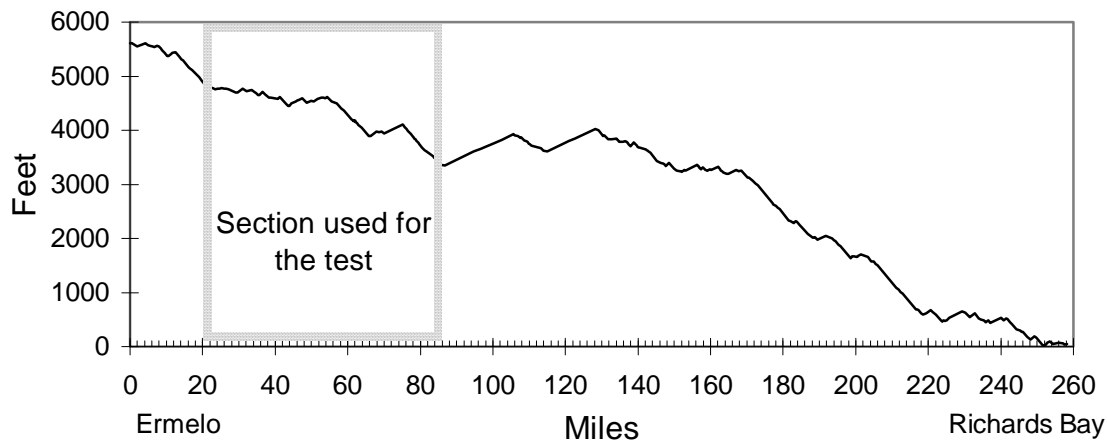
Criteria for evaluation

Intra-train communication, manifested by the combination of ECP braking and distributed power, has the potential for realigning and automating relations among hardware components comprising a train, and hence its overall system performance. The authors thus needed to explore some of the limitations of segmented automatic braking, in combination with distributed power. During the period late 1996 to mid 1997, Spoornet tested various distributed power configurations for the existing 200-car trains. Building on that experience, it ran a 300-car test train in March 1998. Results of the previous tests indicated significantly lower forces and improved brake performance, so that it became reasonable to consider a longer train for two reasons. First, we needed to probe the behavior of a train moving over complex grades. Given a line constructed specifically for heavy haul service, with relatively easy grade changes, it was necessary to substantially increase train length to achieve the requisite complexity. Second, we examined upward operational flexibility, to recover quickly from service disruptions. The ability to operate extra-length trains, with minimum nuisance from training and certifying crews, is attractive.

The following corollaries also came to mind as additional tests of the hypothesis: Is there a simple rule-based technique to guide train-handling decisions. Can one avoid longitudinal force surges by applying predicted amounts of power or dynamic braking at locomotive consists, and applying braking to cars individually or in discrete blocks? Should one apply the automatic brake sequentially as each train segment moves over a crest? Is there any point in swinging a train through sags? Is it rational to power and brake different portions of the same train simultaneously? What magnitude of longitudinal forces should one expect? Can one ultimately automate freight train operation partially or fully?

Test description

The authors conducted the 300-car train test as a first-cut to evaluate specific issues, and surface subliminal ones. The test covered the section Sheepmoor to Comondale, a distance of 64 miles, on the Ermelo-Richards Bay line: It includes a selection of historically difficult crests, without imposing too many severe descending grades that might have proven troublesome on a first trip. Figure 1 shows the relevant line

Figure 1 Line profile

profile segment. The train comprised a leading consist of two Class 11E locomotives, followed by a first 100-car rake, a two-unit instrumentation car, a second consist of two Class 11E locomotives, a second 100-car rake, a third consist of two Class 11E locomotives, and a last 100-car rake. The trailing load was 34,541 tons, with a total train length of 12,380 feet. Maximum speed was Spoornet's normal 50mph on that line.

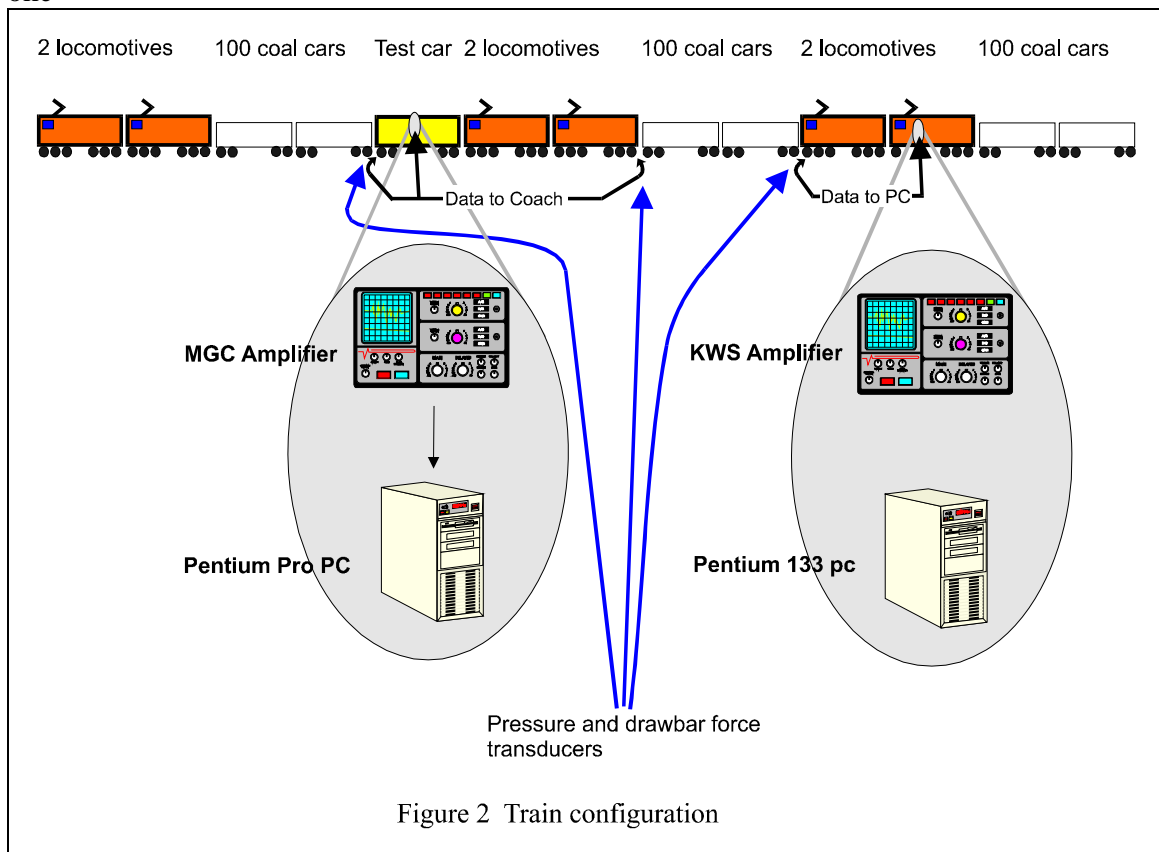
EMD built Spoornet's Class 11E straight electric locomotives, incorporating ASEA electrical equipment. They are type GM5FC, similar to the GF6C locomotives on the Tumbler Ridge line in British Columbia. They are lighter, at 369,000 pounds instead of 390,000 pounds, and operate from a 25kV 50Hz catenary system, instead of 50kV 60Hz. Starting tractive effort is 130,000lb, with a continuous rating of 90,000lb, at twenty-two miles per hour. Maximum output is 5200 horsepower on rail. The rotary discharge cars are drawbar-coupled in pairs, each pair being 79'-2" over couplers. Their tare is 22 tons, they have 92 tons capacity, and ride on radial steering trucks. They have a random mix of ABDW, ABDX and DB60 control valves, and Miner SL-76 drawgear. Brake pipe setting was the Spoornet standard of 80psi.

Normal practice is to supply clients with rakes of one hundred cars for loading. The test arrangement thus endeavoured to minimize disruption to normal operations. It was therefore expedient to divide the automatic brake pipe into three segments: The leading locomotive consist of each segment controlled its segment of the automatic brake pipe. An attempt was made to modify two ABDX control valves back to back to allow an emergency application to pass between segments in both directions. In practice, an emergency application propagated to the next rake only as a service application.

Instrumentation was carried on a test coach located ahead of the second locomotive consist. It comprised a dual Pentium Pro 200MHz personal computer with 64Mb of random access memory. Its analogue-to-digital card was a National Instruments AT-MIO-16E-10. A HBM model MGC signal amplifier, equipped with MC55 modules, measured brake pipe pressure with HBM PD1 differential pressure transducers, and draw bar force with strain-gauged couplers, on the cars in front of and behind the locomotives.

In addition, a similarly equipped 133MHz Pentium personal computer with 32Mb of random access memory was carried in the cab of the trailing locomotive of the leading consist. A HBM KWS 3073 signal amplifier, with similar transducers, measured brake pipe pressure and draw bar force behind that locomotive. The software on both computers was developed in Labview, from National Instruments. The sample rate was 100Hz. Post processing of the data used Microsoft Excel 97. Figure 2 shows the test train and instrumentation diagrammatically.

The authors managed the enginemmen of the three consists by voice radio, from the lead locomotive. Accelerometers, calibrated in kilometers per hour per minute, are standard fitment on Class 11E locomotives. Train handling decisions were informed primarily by comparison of accelerometer readings among the locomotives, and secondarily by coupler forces measured at the above mentioned locations. The three enginemmen sought to maintain the same acceleration at all three locomotive consists, and thereafter sought to manage coupler forces. Where it was not possible to maintain the same acceleration at all three consists, the enginemmen maintained a positive differential acceleration toward the front of the train, to ensure gentle compression, rather than tension, in the train. This was a lesson learnt from the world record train: If necessary, one



should arrange the train design to be able to meet this condition. Allowing the head end to accelerate away from the rear end is extremely risky on a long, heavy train, because it is not a self-limiting condition.

Objective findings

The use of accelerometers, to inform enginemen of the longitudinal condition of the train, proved to be an acceptable paradigm for train handling decisions. At no time could the available range of modulation of power, and dynamic or friction braking, not maintain a positive differential acceleration toward the front of the train. It thus appears that this paradigm could form a basis for automation of train handling. Of course, serious consideration of further development would require theoretical analysis as well as more incisive testing.

The segmented automatic brake pipe delivered according to expectations. The lack of graduated release was to some extent ameliorated by the ability to release the automatic brake one segment at a time. Naturally, such practice is no substitute for graduated release, because it could overheat car wheels if used without information on wheel temperature. Segmented application and release thus introduce the possibility of matching the amount of braking to the requirements of a particular section of a train. Segmentation of the test train was coarse, for the practical reasons mentioned. However, the observed behavior suggested that it would probably not be necessary to segment down to the ideal single car to realize major benefits from the principle.

Distributed power and segmented braking can maintain in-train forces within acceptable limits. Figure 3 shows a graphical display of the forces measured during the

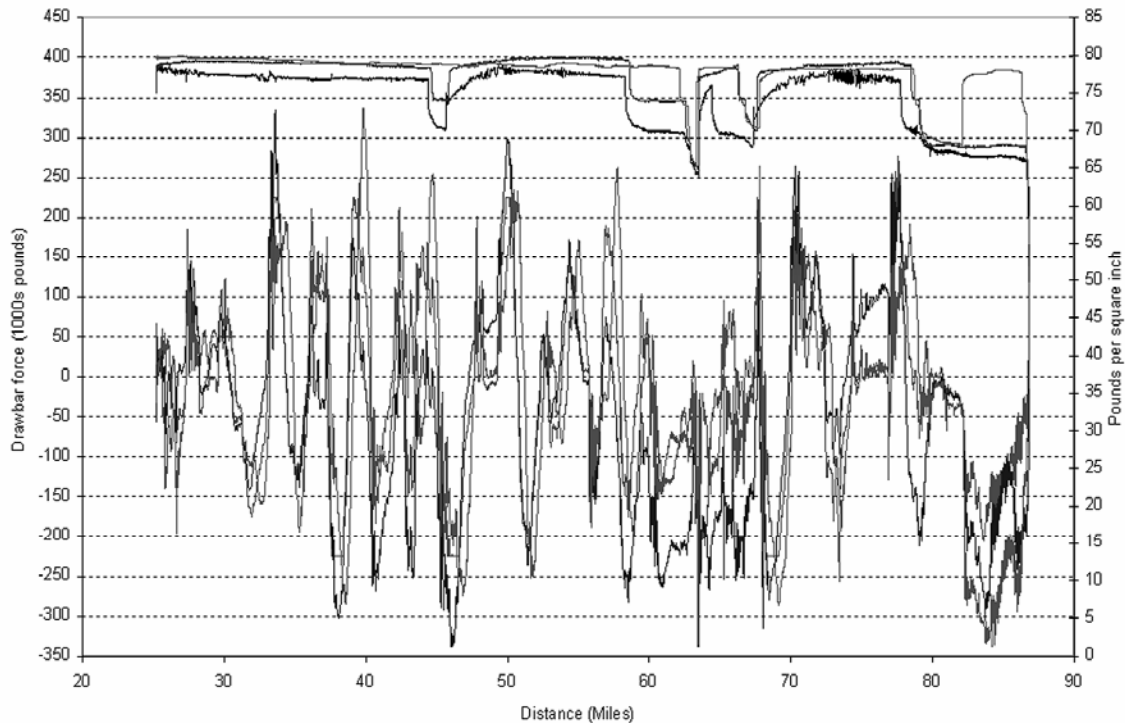


Figure 3 Drawbar force and brake pipe pressure

test run. Initially, maximum draft force exceeded the desired value, but as the enginemen gained experience they reduced it to within that value. Buff force peaked at 170 tons, behind the third locomotive consist, on the ruling descending grade, during a brake application on the first and second segments, but not on the third. This situation was unintentional, but resulted from an apprehensive first application of the automatic brake by the leading crews, as they attempted to reduce tensile forces in the train while traversing a crest. Their apprehension was no doubt compounded by the uncertainty of voice radio communication at a critical juncture. With further experience this would not take place.

With the current 200-car trains, in-train forces over crests are critical, and locomotive engineers must be acutely aware of what is happening in their trains. The test demonstrated the ability to control draft forces in this situation, to lower values than Spoornet currently experiences. However, it appears that there is a trade-off between high compressive forces in sags, and lower draft forces over crests. Regarding the implications for an autopilot, the propensity for high compressive forces in sags suggests the need to compute longitudinal forces in the train, and use such values to moderate the constant acceleration objective function. There are already credible simulations that model train performance in sufficient detail. This is an area that will require further research.

Subjective findings

This area was a source of rich findings, because researchers can possibly not design first-cut tests with sufficient foresight to identify all eventualities. This test was indeed essentially exploratory. First, the 300-car train proved easy to control. It worked easily, contained no surprises, and enginemen quickly grasped the new train handling paradigm. This could in part be a consequence of experience gained on previous manned distributed power test trains, as well as manned combined trains that ran on the same line for several years in the mid 1980s. However, on a rank-order scale, the 300-car segmented-control train was significantly easier to handle than the standard 200-car train, that in turn is easier to handle than the tiger-riding 660-car world record train. Second, handling on long descending grades did not present the expected difficulty, due to the ability to apply the automatic brake segment by segment as the train crested, thus enabling a precise application. This situation may be easier with graduated release, because one can partially release too big an application, but it does not address the fundamental issue. Nevertheless, the use of segmented braking rendered crests, before long descending grades, less sensitive to judgment than normal, thereby demonstrating its potential applicability to automation.

Third, strong central command appeared not to be necessary. On the contrary, one could contemplate decentralized driving coordination. Once all three locomotive engineers had grasped the segmented control paradigm, they based their decisions independently on road knowledge, acceleration at locomotive consist level, and speed at train level. The latter is of course ever present in the permissible speed profile, as determined by diverse track properties. The segmented control paradigm does thus not appear to be unduly sensitive to the level or precision of command.

Last, at no time did the acceleration-based train handling decision rule lead to an empty set. This is particularly important when contemplating automation in an environment where determinism is already acceptable, but fuzziness might be less welcome. Clearly, establishing whether this tentative finding is exhaustive or not will demand much further theoretical and practical research.

CONCLUSIONS

There appear to be advantages in segmenting control of both power and automatic braking, where train length is long relative to the wavelength of grade changes. Theoretically, train handling could then be independent of train length and weight, in the presence of automated smartness at the information level. This could enhance mission reliability through opening the way to supportively or even extensively automating the train-driving task.

ACKNOWLEDGEMENT

The authors express appreciation to the management of COALink for their support of the test that made this paper possible.

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