Safer, Faster, Heavier Trains By Optimising Sensory Feedback To Drivers.

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Abstract. The writer defines sensory feedback and then examines some contextual issues. He emphasises a whole-system perspective, including the train driver, infrastructure, topography plus locomotive and train dynamic characteristics. The paper reports research undertaken, using unobtrusive observation and participant observation. The writer identifies key contributors to sensory feedback and discusses them in train handling situations that benefit from understanding the underlying relations. The paper examines the chronological development of the traction and braking characteristics of several locomotive generations, that provided an opportunity to develop these abstractions. The conclusion is that there appears scope for improving the competitiveness and safety of freight railways through managing train drivers' sensory perceptions.

Introduction

Sensory feedback defined. I define sensory feedback in the present context as a train driver's experience contingent on modulation of locomotive power and braking controls. This paper addresses overall system response, not tactile characteristics of control levers. Direct kinaesthetic feedback is indeed impossible, because locomotive power and braking controls initiate dynamic responses determined by time-dependent functions outside the confines of the locomotive. Indirect whole-system kinaesthetic feedback therefore seems an appropriate description. Some lags can be measured and displayed. For example, an accelerometer may relate locomotive tractive or braking effort to trailing load or grade or both. Similarly, a flow meter may indicate the extent of recharge after releasing the automatic brake. Largely, however, a train driver lacks objective information on the state of a train. Sensory feedback fills this void. Optimised sensory feedback extends a train driver's perception of his or her abilities.

An introductory paradigm. To the author's best knowledge, indirect whole-system kinaesthetic feedback has not been previously addressed in a railway context. The subject therefore requires an appropriate introductory paradigm. It originated while addressing specific engineering problems, yet it is evidently also rooted in ergonomics. Furthermore, although a driver's perception can be managed, significant human constraints and their concomitant ethical implications should be recognised.

Previous related work focused on the driver's environment as a workplace. For example, Wittgens (1) considered several aspects of a closed driver-locomotive system. Duncan (2) examined systems to display internal feedback to drivers, in a similarly closed system. Studies not predicated on open systems must confine their inquiry to interfaces between driver and locomotive. However, the whole system includes the driver as well as infrastructure, topography and, most importantly, locomotive and train dynamic characteristics.

Karwowski's (3) description of many man-machine interfaces as fuzzy seems to open two legitimate approaches to the foregoing issues. Firstly, at low levels of fuzziness, automation may fill information voids and so extinguish the need for sensory feedback, as is progressively occurring in metro railway systems. Alternatively, at high levels of fuzziness, overall system design can tailor sensory feedback to positively reinforce the driver's perceived consequences of his or her actions. I assert that operating heavy-haul and intermodal trains on mixed traffic lines elevates system fuzziness to a high level. This paper therefore addresses the alternative approach.

Objectives. The objectives of the work reported are twofold. Firstly, enhanced productivity and safety render it ergonomically advantageous to give a train driver appropriate sensory feedback. Secondly, it is necessary to integrate total system characteristics to achieve coherent design. The questions may be compounded in environments that regulate technical standards or specific parameters without appreciating the relation between them. However, I do not claim to report new principles. Time has long reduced the mechanics to base technology, but the railway industry still does not understand and appreciate the competitive value of sensory feedback to the same extent as, for example, the motor industry.

Methodology. This paper reviews a groping effort to understand and manage what at first seemed to be an intractable situation. The issues originated in empirical evidence accumulated during locomotive commissioning and train handling development for unit freight trains, later heavy haul trains and ultimately high-speed intermodal trains. Train drivers have lay comprehension of the physical relations underlying their task. They therefore neither interpret their perceptions nor articulate possible relations adequately. Their responses also betray that they frequently couch their perception of inquiry in suspicion. My research was consequently spread over many years, using both unobtrusive observation and participant observation. Rigid insistence that information gleaned be applied only in a beneficial sense secured co-operation. Inability to simulate sensory feedback seriously constrained progress. Nevertheless, successive locomotive generations each offered opportunities to implement incremental improvements. Within the fidelity limits of simulators, future development employing simulation may converge more rapidly on satisfactory solutions.

The practical context. Rail transport occupies four eminent domains at present. They are light- and heavy metro, high-speed passenger, intermodal and heavy haul. The latter two tend to share infrastructure with other operations. This imposes substantial demands on system compatibility. Ideally, infrastructure, rolling stock and driver training requirements should relate through a parsimonious set of common factors. The scope of Spoornet's activities illustrates the nature of the problem. Spoornet operates a national freight railway network in South Africa. Heavy haul trains convey bulk minerals from major inland mines to harbours at Saldanha and Richards Bay. Such trains convey 26 tonnes per axle on dedicated lines and 20 to 22 tonnes per axle on shared lines. The Ermelo-Richards Bay line also conveys significant other traffic. Major industries are located both in the Pretoria-Witwatersrand-Vereeniging (PWV) complex and in coastal cities. Intermodal services connect the PWV complex with Durban, Port Elizabeth and Cape Town. These service the mini-container, ISO container and swap-body niches, marketed under respectively the PX, CX and Bimod brand names. Spoornet's loading gauge does not permit double-stacked containers. The lines mentioned are all colour-light signalled. Earlier systems used three aspects, of which one is ambiguous, without necessarily providing braking distance between signals. Later systems used multiple aspects to eliminate ambiguity and provided braking distance between signals. Both systems currently exist on contiguous networks. Design braking distance is nominally 1200 meters, except on Sishen-Saldanha where it is 2000 meters. Current maximum train tonnages and operating speeds are respectively 20 000 tonnes at 80 km/h and 2000 tonnes at 100 km/h. A recently introduced

120 km/h prototype service between Johannesburg and Cape Town, which presently conveys approximately 800 tonnes, will probably convey 1500 to 1800 tonnes when the full locomotive fleet is in service. This mix of train and operational characteristics offered ample scope for research.

Key sensory feedback elements

Its nature. Murrell (4) pointed out that man can sense minimal stimulae from a wide range of sources simultaneously and integrate these signals to produce a complete picture of an event. Since almost infinitely gradated combinations of changes occur, it might be difficult, if not impossible, to program a machine to cover the wide range of eventualities that a person can cover. Without a paradigm, intuition suggested that rationalising indirect kinaesthetic feedback would reduce the fuzziness of information sensed by a train driver and so enhance the level at which he or she can work. In a locomotive other sources of sensory feedback are also present, dominated by auditory feedback. However, my subjective evaluation is that auditory feedback is a valuable augment to other feedback, but not a substitute for it.

Longitudinal acceleration. Train drivers rely heavily on their sense of longitudinal positive or negative acceleration for basic train handling. Harsh train action can exceed 5g in the cab of a locomotive. Service braking retards a heavy freight train at 0.01-0,05 g. The acceleration of a heavy train passing over a crest is approximately 0.001 g. Discounting involuntary response to slack change, the acceleration range encountered is thus 50 to 1. At lower accelerations, the frequency is also very low, but auditory feedback reinforces the driver's perception of changing speed. Nevertheless, the range of stimulae that a driver can perceive is amazing. These parameters illustrate one challenge to simulator designers because, among other criteria, the ability or otherwise to generate realistic stimulae over a 5000 to 1 acceleration range determines simulation fidelity.

Response to lever movement. Drivers frequently operate major controls, such as accelerating lever (or throttle), dynamic brake and automatic brake, while other tasks divert their primary attention. Some examples are observing lineside signals, communicating by radio, or visually judging the precise stopping point of a train. It is therefore important that the overall system responds rationally, or according to intuitive expectation, to control modulation. Response is irrational if dead handle movement is present. Dead handle movement occurs when the characteristic curve associated with a demand level between zero and maximum does not mimic the characteristic envelope of that function.

The automatic brake. Where applicable, this discussion is predicated on direct-release air brakes. Some aspects may therefore be invalid if applied to graduated-release air brakes. This paper will not discuss the automatic brake *per se,* although it is definitely relevant. The contribution of system state-of-charge to fuzziness, and hence also to the value of alternative systems that accelerate response, deserves recognition. However, both time and compatibility constraints have honoured the present direct-release air-brake system characteristics. Unless deployed in dedicated service, marginal additions to a fleet are therefore not easily tuneable for specific purposes. Typically, feasible brake ratio and brake block characteristics define the limits of such tuning. In principle, subject to the constraint of adequate stopping ability, the lowest possible brake ratio is preferable.

Handling fluidity. On curved or easier portions of long descending grades, where there is insufficient time to recharge a direct-release brake system after release, the train brake effectively becomes a fixed portion of total braking effort. The dynamic brake provides a complementary variable portion. The contribution of the dynamic brake thus constitutes the variable portion of total braking effort. Handling fluidity is adequate when the variable portion of total braking effort fully overlaps the variance inherent in any portion of descending grade. The converse, stickiness, occurs when the grade variance exceeds or does not match the range of variability of the total braking effort. Figures 1 and 2 depict these conditions. Dynamic brake power should therefore be adequate at the speed envisaged for a particular service. Of course the brake block coefficient of friction should also not vary significantly with speed.

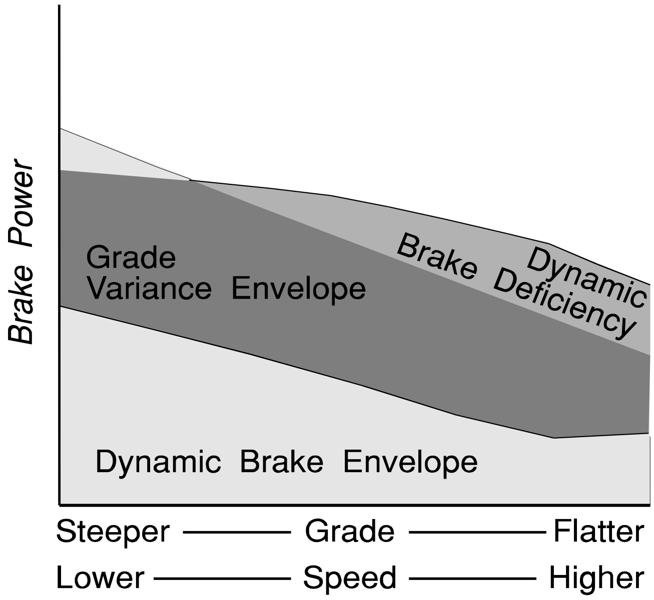


Figure 1

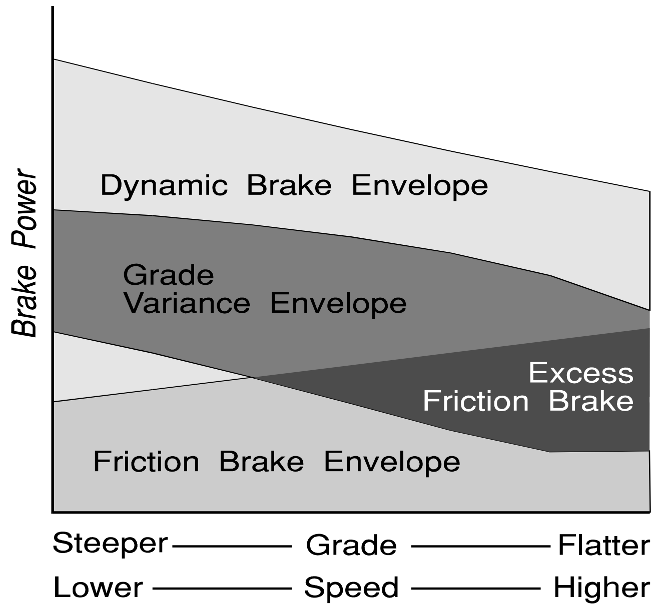


Figure 2

Time delays. Various sequential time delays have over the years become established in locomotive power and dynamic-brake control systems. They typically relate to setting-up and initialising motoring and braking circuits. Time delays are part of locomotive lore, sometimes enforced by interlocking and sometimes upheld as sound practice. Depending on their length, they may impair or enhance indirect kinaesthetic feedback. Traction or dynamic braking can be set up in five to ten seconds on diesel-electric locomotives and in approximately one second on solid-state straight-electric locomotives. The five-to-ten-second range is acceptable for most heavy-haul situations. In high-speed intermodal service, time delays longer than one second to set up traction or braking cause respectively vexation or trepidation. It seems that time delays on locomotives intended for both intermodal and heavy-haul duties should be speed dependent.

Ramp rates. Early-design straight-electric direct-current locomotives responded jerkily to direct-on-line traction and dynamic braking modulation. First-generation diesel-electric locomotives exposed train drivers to the gentle power build up that inheres in diesel engines. Gentler response earned recognition for facilitating starting from rest and over-the-road handling. Ramp rates and appropriate parameters received acknowledgement as relevant to locomotive design. With the arrival of solid-state power electronics for straight-electric locomotives, diesel-electric locomotive ramp rates provided the initial benchmarks. The traction and braking ramps were empirically optimised on classes 7E and 10E locomotives (discussed later), but with somewhat sharper response than diesel engines could support. At that time, the classes 7E and 10E were in heavy haul service. Later, intermodal services deployed some of them in a substantially higher speed regime. Thereupon some intermodal drivers perceived the powering-up ramp to be too slow to facilitate adequate sensory feedback of traction application through sags. Traction can ramp up in five to ten seconds on straight-electric locomotives. It takes fifteen to twenty-five seconds on diesel-electric locomotives. Dynamic braking can ramp up in approximately five seconds on all the locomotives mentioned, although this is somewhat too rapid for much heavy-haul train handling. This situation suggests the need for speed sensitive ramp rates.

Correct practice. Appropriately shaped dynamic-braking characteristic envelopes can prod drivers toward preferred train handling techniques by effecting awkwardness when they deviate therefrom. For example, on steep descending grades, stopping distance rather than thermal energy dissipation imposes the critical constraint. Whereas higher speeds on easy descending grades demand lower brake ratios to constrain train wheel thermal loading, this ploy does extend stopping distance. Thus the brake ratio requirements for steep and easy descending grades contradict each other. When choosing lower brake ratios, as Spoornet usually does, drivers need encouragement to make at least a minimum automatic brake application on steeper descending grades. The class 38 locomotive, discussed later, encourages this choice by trimming dynamic braking effort between 25 and 40 km/h.

Relevant train handling situations.

Starting. When a train comes to rest, the slack may be unevenly distributed. This phenomenon is a function of topography, brake demand modulation and brake system response. A newly marshalled train has similar characteristics. When starting from rest, stretched, bunched, or irregularly stretched and bunched slack may be present. Consequently, locomotives pick up a load erratically. After overcoming initial rolling resistance and while the head-end is moving, the driver should maintain very low speed until he or she has taken up all slack. If the locomotives meet sufficient additional resistance, when the moving portion of the train reaches an already stretched but still stationary portion of the train, the train will stall if the tractive effort curve is insufficiently steep. This happens when a driver is inattentive or distracted, and causes anxiety when starting heavy loads on ruling ascending grades. The rate of change of tractive effort with speed at starting should be steep enough to sustain movement while stretching slack, irrespective of the state of the slack.

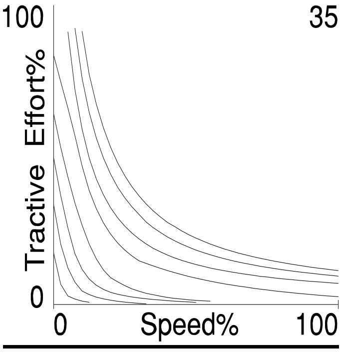
Sags & crests. Sags, which trains negotiate at relatively high speed, demand fine dynamic brake gradation, quick transition to motoring and rapid traction motor current ramp-up. The longer and the heavier the train, the slower the procedure occurs. However, if the sequence is too slow through being artificially retarded, the train may unnecessarily lose speed on the next ascending grade. It is nevertheless the situation that demands the fastest response. It appears that the optimum solution is to define time delays and ramp rates as a function of speed. By contrast, trains tend to negotiate crests relatively slowly, because they follow long ascending grades. By similar reasoning, the speed on the next descending grade is usually higher than the speed over the crest. Hence there is sufficient time to accelerate a train before needing the dynamic brake. The wind resistance of intermodal trains is so high that drivers can make a slow transition to dynamic braking far beyond a crest. Therefore time delays and ramp rates are not at issue on crests.

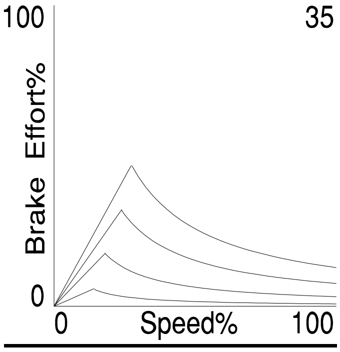
Descending grades. On descending grades, curve compensation amplifies the inherent variance in effective gradient. Therefore the effective gradient on long descending grades is contingent on both topography and curve compensation. Given sufficient fluidity, the driver should make a constant automatic brake application and thereafter modulate the dynamic brake as required. The slope of the dynamic braking effort versus speed characteristic is of interest here. In generic terms, braking effort may rise or droop (or indeed do anything the customer desires with microprocessor technology). The two fundamental characteristics present a dilemma. A rising dynamic braking characteristic is inherently stable, but dead handle movement may limit the modulation range towards maximum speed, giving almost an on-off rather than sensitive characteristic. A drooping braking characteristic enhances sensitivity by avoiding dead handle movement toward maximum speed, but requires increased driver concentration. Although the latter may cause subliminal uneasiness, Spoornet's drivers have not yet articulated a problem at the conscious level.

Precise stopping. Precise stopping requires an ability to increase or decrease braking force as a train approaches the target. It is easier to stop precisely on a level or ascending grade than on a descending grade. The latter case constitutes a base load that effectively reduces braking variability. The precision expected depends on the train type and the gradient. For intermodal trains, stopping within a five meter space is acceptable. Twenty meters is acceptable for long, heavy trains, although many drivers stop with greater precision. To relate perceived remaining braking distance to the target, the driver modulates braking demand. Confidence-building indirect kinaesthetic feedback demands immediately perceptible response. The procedure is awkward when a driver may only increase braking effort, but can not reduce it. Typically, a driver relinquishes discretion and commits a train to the brake system the moment he or she initiates the final brake application. Discretionary latitude is adequate if the driver need not initiate a final brake application at higher than 15 km/h. The dynamic brake should therefore have extended range down to that speed.

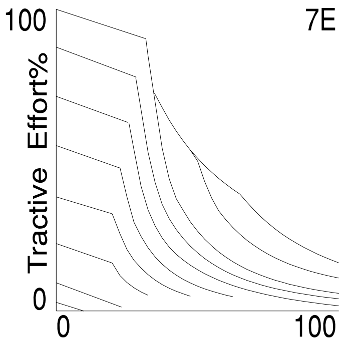
Some examples.

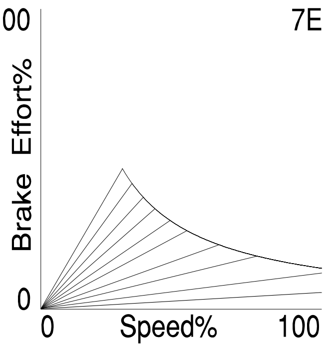
A benchmark. Some examples from Spoornet's locomotive chronology will now illustrate issues raised in the foregoing discussion. The order of presentation follows the order of development. The diagrams are non dimensional so that particular locomotive power ratings do not confound the principles. A first generation diesel-electric locomotive provides the benchmark. Adhesion, not electronic tailoring, limited its steep tractive effort curves at low speed. Drivers appreciated the ease with which it started loads from rest. The engine governor ramped power up gently. Rational response followed throttle and dynamic-braking handle movement throughout the speed range. However, only the relatively slow speeds of the day rendered the slow transition between dynamic braking and power acceptable.



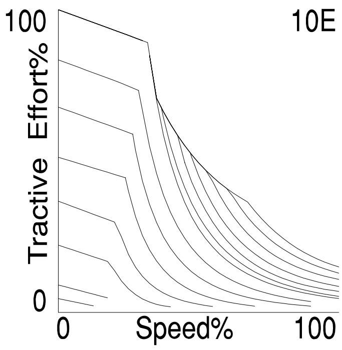


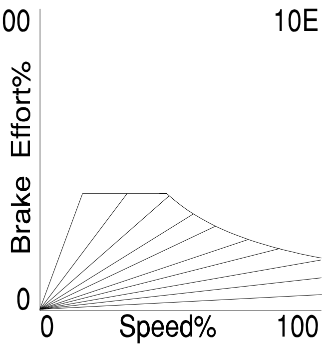
<u>Class 7E</u>. Spoornet's first AC thyristor-controlled locomotives reveal influence from contemporary diesel-electric characteristics. The power-electronics current limit flattened the top of the tractive effort curve, and intermediate handle positions generally followed the outer envelope. Some dead movement exists near maximum handle position at lower speeds. Reservations concerning high longitudinal compressive coupler forces pegged maximum dynamic braking effort. Although thyristor control facilitated significantly higher traction adhesion, the absence of extended range unfortunately limited the power of the dynamic brake. Consequently, train handling feels sticky in some circumstances. The slope of intermediate handle position dynamic braking curve is consistent with that of constant excitation regenerative braking. The latter is more stable on descending grades, but at the expense of insensitivity and dead handle movement at higher speeds.



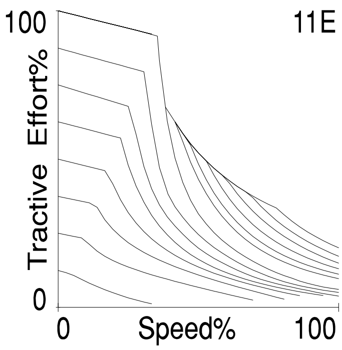


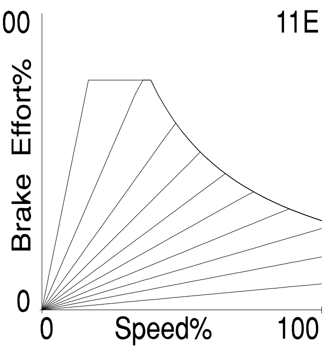
<u>Class 10E</u>. Spoornet's first DC chopper-controlled locomotives introduced extended range dynamic braking. This admitted somewhat higher dynamic brake power rating at higher speeds without risking excessive longitudinal coupler forces at lower speeds, to minimise sticky handling. They were specified for heavy haul service and the electric brake rating is thus sub-optimum for the intermodal trains that some of them now work. Dead handle movement in power and braking is similar to that of the class 7E. During this period it emerged that intermediate handle positions at low speed should not repeat the slope of the tractive effort envelope. The latter slope is too flat to preempt stalling when taking up slack from rest. Class 14E and subsequent locomotive classes address this problem.



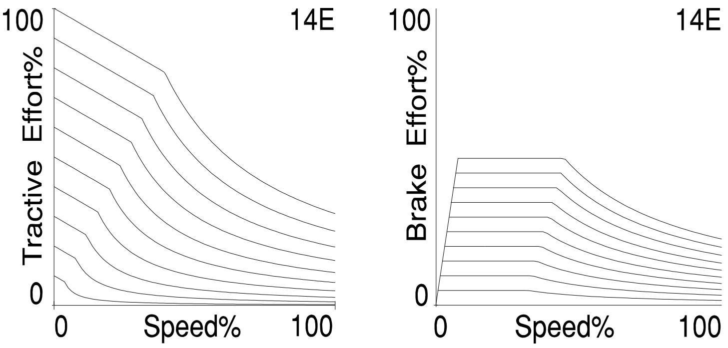


<u>Class 11E</u>. The dynamic brake rating of Spoornet's class 11E is higher than the traction rating, among other to eliminate stickiness. This feature stimulated developments that later laid the foundation of energy saving and intermodal train handling. However, the requirement for consistency with the class 7E perpetuated dead handle movement and insensitive control at higher speed.

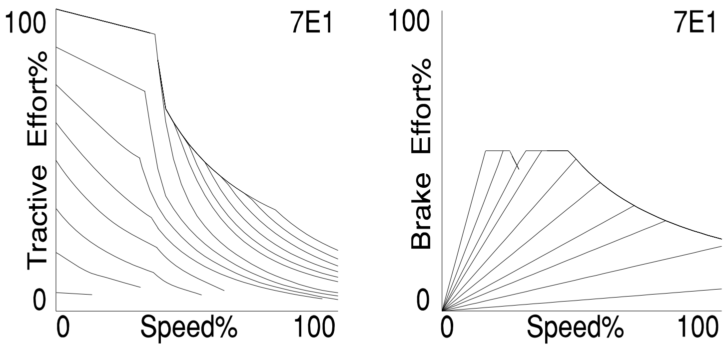




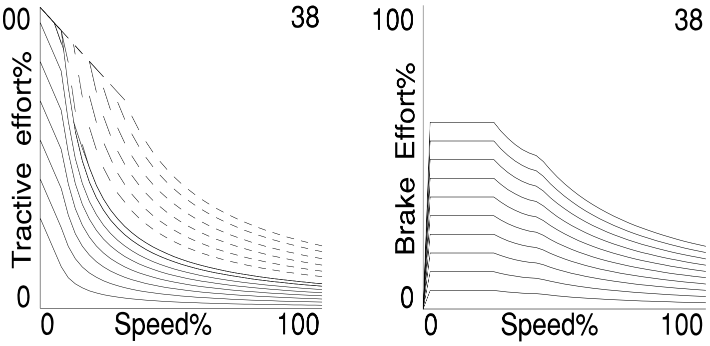
Class 14E. Although originally intended as universal locomotives, Spoornet's three prototype 140 km/h locomotives service what is now an intermodal market. A large fleet of other locomotives dominates the operating environment. Therefore driver support features such as automatic train control are not feasible. The infrastructure, inherited from the past, reflects period design standards. The driving task involves handling high performance intermodal trains over give-and-take terrain. Visual stimulae provide prime inputs to a driving style akin to driving a road vehicle. Hence it is important to minimise a driver's ergonomic load by minimising control system fuzziness. This demands sharp response from dynamic and automatic braking. The starting tractive effort curves are steep, and the intermediate dynamic braking characteristics mimic the characteristic envelope. However, rated at less than full traction motor rating, the dynamic brake is sub-optimum by current norms. This situation transfers more braking effort than usual onto wagon tread brakes. The lengthy, seven-second delay to set up dynamic braking compounds the problem. This also tends to transfer braking to the automatic brake, which drivers perceive to respond faster.



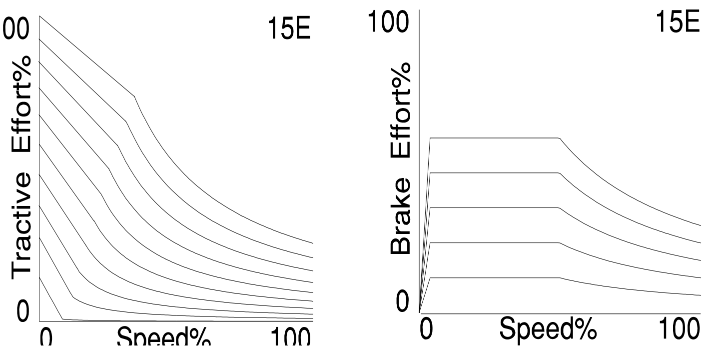
Modified class 7E1. To augment the capacity of class 11E locomotives, Spoornet modified its class 7E1 locomotives to work 200-wagon trains on the Ermelo-Richards Bay line. The outer envelope of the modified locomotive represents two-thirds of a class 11E, so that six modified class 7E1s can substitute for four 11Es. It is not technically possible to operate these classes in multiple. The modification improves but does not optimise the intermediate handle position characteristics. This was a constraint imposed by existing locomotives being modified. Steepened tractive effort curves reduce stalling during starting. A smaller gap between dynamic braking intermediate handle positions at higher speed increases sensitivity. Nevertheless, the redesign could not expurgate the constant excitation rising braking effort characteristic and the concomitant insensitivity.



<u>Class 38</u>. Spoornet acquired its class 38 locomotives to expedite service to customers with private-sidings. They are rated at 1500 kW, with a back-up diesel engine of 750 kW to facilitate operation off electrified sections. They incorporate accumulated experience plus the almost limitless scope of microprocessor-controlled three-phase traction technology. Innovation has now translated control issues from the feasible to the conceivable. Deviations from the ideal originate from lower power in diesel mode than in electric mode, and in the limited dynamic brake capacity that backs up the regenerative brake. Aversion to dead handle movement was compromised to obtain consistent response to control modulation, in electric or diesel mode, in traction or dynamic braking, irrespective of overhead line receptivity. Thus in diesel mode the accelerating lever has dead movement between 750 kW and 1500 kW. In dynamic braking in diesel mode or when the overhead line is unreceptive, dead handle movement occurs between the 1000 kW stack rating and the 1500 kW locomotive rating. The speed is typically low in diesel mode and only line receptivity limits regenerative braking in electric mode. Any dead handle movement is therefore consistent with expectations and should be imperceptible in normal operation. Indeed, it provides logical feedback concerning the system status. The slope of the tractive effort is steeper at lower speeds, and the intermediate dynamic braking handle position characteristics mimic the outer envelope to give sensitive response throughout the speed range.



Class 15E. For the future, Spoornet's proposed class 15E idealises locomotive traction and braking characteristics to support rational train handling through optimised indirect kinaesthetic feedback. If applied in conjunction with the handleability construct presented previously (5), the writer believes the knowledge exists to elevate train driving and handling into the realm of its major competitor, road transport.



CONCLUSION.

The writer hopes that this paper will stimulate further description and understanding of the phenomena train drivers experience while they drive trains. I have tried to identify and describe some key issues, and have alluded to some others, but I recognise that my effort is not exhaustive. Because the underlying theoretical relations are incompletely understood, the choice of design parameters can not be conflict-free. Regrettably, this state of affairs begets judgmental rather than deterministic solutions. Railway administrations tend to justify such issues as discretionary by invoking the railway tradition of uniqueness. However, only a fine distinction seems to separate discretion from parochialism. In an industry that is fending off serious competition from road transport, I believe that agreement on optimised sensory feedback can significantly contribute to system rationality, consistent driver training and reliable performance, and ultimately to enhanced safety and heavier, faster, more productive trains.

ACKNOWLEDGEMENT.

The writer gratefully acknowledges the patient assistance of Alan Cortie and Georg Hettasch, who generated the figures presented here.

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