A challenge to traditional perspectives on freight railway energy provisioning

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1. Introduction

This paper will examine some important drivers of the choice between diesel- and electric traction. The reasonably well-defined options of the past have become embroiled in the turbulence of railways attempting to position themselves to compete and survive in a single, global, economy, rather than in individual national economies. The author will first review some of Spoornet's experience as a foundation for an analysis, then examine trends that are set to influence future developments, and finally integrate perspectives on where freight railway energy provisioning may be headed.

2. Spoornet's heavy haul experience

2.1. Overview

Spoornet's experience with both diesel- and electric heavy haul, over almost three decades, has contributed significant organizational learning. Some learning was gained with diesel and 3kV direct current operations, hauling trains in the 8-10 000 tonne range with locomotive consists rated at up to 12MW, on general freight lines. Other learning was gained with diesel, and 25- and 50kV alternating current operations, hauling trains in the range 10 000-20 000 tonnes with locomotive consists rated at 12-18MW, on dedicated lines.

Spoornet has major achievements in both diesel- and electric heavy haul. Railways elsewhere have replicated some of its learning. Other learning may diverge, due to differences in factor costs of production, in particular those of diesel fuel and electric energy. However, when contemplating the future, it is necessary to criticize the past constructively, so as not to repeat its mistakes. This paper attempts to do that. The following paragraphs review the basic attributes of diesel- and electric traction. Figure- and Table numbers refer to the PowerPoint presentation that accompanies this paper in the Proceedings.

2.2. Electric traction

2.2.1. Overview and pros

Electric traction offers three significant pros, which enabled it first to challenge the supremacy of steam traction, and thereafter to defend itself against diesel traction.

The first pro is *relatively high balancing speed*, due to the network power of an external energy supply generally exceeding the output of the diesel engine that will fit into a locomotive. This advantage reduces, and may even disappear, when the installed power of a heavy train is sufficient to challenge the installed capacity of its energy supply network.

The second pro, related to the first, is *constant adhesive mass*. An external energy supply makes the full permissible locomotive mass available for traction, in contrast to the variable mass of a diesel locomotive, which depends on the amount of fuel in its tank.

The third pro is *relatively low energy usage cost*. This pro is strong in South Africa, but is not necessarily so elsewhere in the world. Furthermore, the author argues in Paragraph 3.4 that one can not take the stability of energy pricing for granted.

Several cons challenge these pros. It is useful to categorize them into two groups. First, there are those which relate in a systemic sense to the technology of supplying external electric energy to trains. They inhere in the nature of railway electrification networks, and attend such systems irrespective of the source of energy, whether it is conventional or alternative. Second, those that relate in an artifactual sense to the technology of converting electrical energy from an external supply into tractive effort. They inhere in the design of electric locomotives.

2.2.2. Systemic cons

The first systemic con is *low scalability*, because both substation capacity and conductor size should grow proportionally to demand, whether that is train size or service frequency. It is not in the nature of substations and conductors to grow in small increments, as in the case of adding more diesel locomotives to haul a heavier train.

The second systemic con is *unpredictable external supply dynamics*. The dynamic interaction among several trains simultaneously drawing- or regenerating power can perturb the network sufficiently to trip out equipment or degrade tractive effort stability sufficiently to induce high longitudinal forces in trains. The attendant voltage spikes incur the additional cost of input filters to protect power electronic devices, and may slow the rate of adoption of new technology such as IGBTs. Bunching of trains after service disruption may encounter peak energy supply constraints. In the limit, it may even become difficult to distinguish between a heavy load and a fault on a direct current network.

The third systemic con is *operation within, rather than at the limit of, the tractive effort-speed characteristic*, at low line voltage. This can lead to train breaks and/or high aggregate tractive forces applied to the track structure. Peculiar load sharing among distributed power- or manned helper locomotive consists may aggravate the problem.

The fourth systemic con is *tractive effort interruptions,* while traversing injudiciously located neutral sections on alternating current networks. They may initiate longitudinal disturbances that, if they do not part a train, elevate the stress on the driver to a critical level.

The fifth systemic con is the *problematic nature of regenerative braking in freight service*. Although regenerative braking may be attractive in a high diversity network serving many passenger and/or freight trains, it becomes less attractive in a low diversity network dominated by heavy freight trains. For maintenance purposes, double track direct current catenaries are typically not coupled, thus precluding the obvious objective of reusing regenerated energy internally by transferring it from descending to ascending trains. Furthermore, electricity suppliers are by nature reluctant to buy back energy. If they do, they impose qualitative and quantitative constraints, and tariffs that reflect their monopolistic power. It is thus frequently not economically worthwhile or physically possible to regenerate energy during braking, which renders potential savings elusive. This state of affairs also implies that to design heavy trains with a specific, reliable, balance between friction- and electric energy dissipation, it is necessary to incur the additional costs of providing electric locomotives with straight- or blended rheostatic braking. Spoornet has not fully maintained regeneration absorption equipment in recent years, but the ability to regenerate depends on line voltage, which rapidly rises to the 4kV limit in the absence of demand from other trains. One repercussion is a supply voltage variance that is less than friendly to power electronics devices.

2.2.3. Artifactual cons

The first artifactual con is *relatively low mission reliability*. It is compromised by equipment trip-outs that need a train to come to rest before resetting. Line voltage disturbances and interruptions are frequently involved. The problem is aggravated by heavy haul services that need several locomotives in multiple-unit, and becomes a particularly critical issue for trains that are designed to operate with distributed power. Spoornet has already operated manned helper locomotives over extended periods of time, but the presence of a crew on every locomotive consist tempered the problem. At time of writing, Spoornet is in the process of implementing a distributed power pilot scheme, piggybacking on the wireline of electronically controlled pneumatic braking. There is some trepidation regarding the ability of electric locomotives to deliver the mission reliability required.

The second artifactual con is the *relatively high capital cost of locomotives*, due to their originating in a relatively low volume market (Cortie, 1998) serving predominantly public sector railways. The latter have seldom tested their business model against the requirement of a market-driven return on total capital invested.

The third artifactual con is the *relatively high capital- and operating cost of external energy distribution infrastructure*. The investment in substations and catenary drives up both the break-even traffic volume and the risk associated with investment in immovable assets.

In summary, Spoornet has found electric traction generally competent, but not without limitations in heavy freight service.

2.3. Diesel traction

2.3.1. Overview and pros

Diesel traction established heavy haul in South Africa, first conveying ore from mines in the Northern Cape to the harbour at Port Elizabeth, and later founding both the Sishen-Saldanha iron ore export line and the Ermelo-Richards Bay coal export line. It offers three significant pros.

The first pro is the *relatively low capital cost of locomotives*, due to their originating in a relatively high volume market serving private sector railways. The intensely competitive North American railway industry sustains a high-volume production base (Cortie, 1998). Both operators and suppliers have successfully tested their business models against the requirement of a market-driven return on total capital invested. The economic advantages of this circumstance are exportable, despite necessary changes to track gauge and vehicle profile, to Southern Africa- and other markets.

The second pro is *high scalability*. The number of diesel locomotives per train, and hence its tonnage, is limited only by brake system responsiveness, distributed power capability, and the physical constraints of yard- and crossing loop length. This pro is applicable also to the bunching of trains following disruption of a service.

The third pro is *stable tractive effort*. Smoothly modulated power from an on-board diesel engine minimises longitudinal disturbances to trains. This in turn reduces the risk of train partings and undue train driver stress.

The fourth pro is *relatively low capital- and operating cost of energy distribution infrastructure*, due to refueling facilities being concentrated at discrete points. This is possible because the locomotive stores fuel on board, rather than requiring a continuous external supply.

2.3.2. Cons

As in the case of electric traction, diesel traction also has significant cons. The first is *relatively low balancing speed*, due to finite size and mass constraints on the diesel engine itself plus its fuel tank.

The second con is *variable adhesive mass*. The diesel engine and fuel tank contend for a share of the permissible overall locomotive mass. The mass available for traction thus depends on the fuel tank capacity and on the amount of fuel in it.

The third con is *relatively high fuel cost*. This has been a strong driver of railway electrification in South Africa.

In summary, Spoornet has found diesel traction competent in heavy freight service, but high local diesel fuel prices have circumscribed its applicability.

3. Some relevant business trends

3.1. A shift in ownership from public- to private sector

There is a distinct global trend to shift ownership of railways from the public- to the private sector. The norm is now business-driven enterprises, operating under commercial law, as the best way to produce competitive goods and services in national and international markets (Thompson, 2000). Electric traction is not generally associated with equity-driven railways. It is associated rather with public sector railways. On the other hand, diesel traction is generally associated with railways in the private sector (Van der Meulen, 1999). Indeed, after passing from public- to private ownership, railways may even de-electrify (e.g. TFM in Mexico, recently). Passenger railways, either high-speed intercity or city rail, that satisfy the economic expectations of their stakeholders (where satisfaction does not necessarily equate to profit), typically operate on their own dedicated infrastructure. Their energy distribution preference, generally by means of electrification, is clear-cut by virtue of the intensity of such services, and therefore outside the scope of this paper. Furthermore, economic viability is not associated with monolithic freight- and passenger railways. Economically successful railways are dedicated to one or the other (Van der Meulen, 1999).

Globalization is thus driving railways to occupy specific niches in which they possess robust competitive advantage. What then is the prognosis for freight railway energy distribution, whether external or on-board, in the new economic milieu? It appeared opportune to trace the implications of this question upstream in the energy supply chain in this paper.

3.2. An awareness of business risks

The aforementioned shift in ownership from public- to private sectors has heightened awareness of several business risks associated with new investments in railways.

First, the business risk associated with mobile assets, such as locomotives, is relatively low because the probability of redeploying them elsewhere, if business conditions change for the worse, is high. The investor community is thus willing to fund such assets. By contrast, the business risk associated with immovable assets, such as right-of-way, formation and track, signalling, and electrification infrastructure, is relatively high, because the probability of redeploying them elsewhere, if business conditions change for the worse, is low. The investor community is thus reluctant to fund immovable assets. The operator is thus required to fund such assets internally, or be obligated to sovereign guarantees to cover loans therefor. Sovereign guarantees exist only as an adjunct to state ownership, which may explain why the higher capital cost of external energy distribution has typically been associated with state railways.

Second, the fixed cost of an electrified railway network is higher than that of a dieselized railway network, due to the additional investment in energy distribution infrastructure. Increasing the ratio of fixed cost to total cost drives up the breakeven traffic volume, and hence drives up the business risk, of an electrified route.

Third, allocation of the common fixed cost of electrification infrastructure, and of the variable costs of energy metered at substations and maintenance of the electrification infrastructure, to specific trains or operators, is fraught with difficulties. This leads to arguable rather than incontestable allocations, which increase the business risk associated with the one-to-many relationships that characterize open access.

It therefore becomes apparent that the business risks perceived by private sector investors will spur a review of the way that railways provide traction energy to trains.

3.3. Rail freight eminent domains

Railway freight traffic falls into two distinct categories—heavy haul and intermodal, of which container traffic is a major sub-set. On the one hand, heavy-haul of bulk commodities is subject to source competition among several countries, hence there is downward pressure on length of haul. Few heavy haul railways, predominantly those in the public sector, are electrified: The majority depends on diesel traction. On the other hand, globalization of trade is re-shaping transport requirements. The container will be the global transport unit—it is vital to achieve full compatibility with other modes (Sharma, 2000). One may also add *full competitiveness* as a fundamental requirement. The railway sector of intermodal traffic is therefore subject to modal competition and/or intermodal alliances. It is usually intensely competitive, with lean profits. Where it is commercially viable, it tends to be conveyed by long, relatively heavy, double-stacked trains over long distances. It is however a growing niche, in a force field that tends to increase length of haul—which is eminently suited to railways. Container- or intermodal trains also operate at relatively low speed (around 120km/h maximum), among other, due to the unknown centre of gravity height rendering dynamic behaviour more variable than for homogeneous bulk commodities.

These drivers, together with those unique to passenger traffic, have separated viable freight- and passenger traffic (either intercity or city rail) into distinct domains. Freight rail will have to pay its way in corridors where heavy haul and/or intermodal traffic alone can justify the investment risk. In this context, conventional catenary impedes double stacking of containers, thereby increasing the already relatively high business risk associated with electrified freight routes, by excluding a market segment with attractive growth potential.

3.4. Energy pricing stability or instability

3.4.1. Current tax regimes

The author examined the global price spread of *automotive diesel for commercial use* and *electricity for industry* (International Energy Agency, 1999), with respect to the ex-tax price and total tax. The total price to the consumer is the sum of ex-tax price plus total tax. Figures 1 and 2 depict the findings.

Note that, around the world, the cost of producing and distributing energy, whether diesel or electricity, lies within a relatively narrow band. One should expect some differences in production and distribution costs, and this is indeed evident. However, diesel and electricity are clearly subject to different tax regimes. Taxes on electricity vary from zero to a very small percentage of the ex-tax price, whereas taxes on diesel fuel vary from a small percentage of the ex-tax price to several multiples thereof.

This author does not intend to examine the rationale behind taxes on diesel fuel, but rather suggests that their historical origin, namely to fund road infrastructure, eventually became obscured by governments’ fiscal policies and ideological aspirations. When the total tax is more than marginal, or is even the major constituent of the total diesel fuel price, the latter represents an instrument of government policy, as much as it represents a rational input into economic decision-making. This moves the rate of taxation on diesel fuel into global mainstream economics.

3.4.2. The influence of globalization

Globalization tends to erode economic differences among countries, due to competition among them. The pressure that the Internet and disappearing borders place on national tax systems is driving many governments to reconsider the huge tax burden they place on their citizens and businesses. Hence the new tendency for tax regimes to converge (Cavallo, 2000). Furthermore, dollarization (where prices are quoted in US$ along with, or instead of, a local currency) and currency unification (such as creation of the Euro), tend to highlight national differences among consumer prices for the same item. Harmonization of taxes and visibility of consumer prices in a single, commonly understood, currency is unlikely to drive lower prices up—experience has demonstrated that it tends rather to drive higher prices down. Both trends will tend to align diesel fuel consumer prices among countries.

In South Africa, among other, these trends have already become reality. The February 2000 national budget reduced income tax thresholds and marginal rates, and the government was willing to absorb a portion of an extraordinarily high petrol price increase that was implemented in April 2000. However, what used to be a comparatively straightforward decision regarding long-term investment in locomotives and energy distribution assets, has now acquired the potential to turn into a financial quicksand before such assets have been amortized. One should thus expect major instability in relative factor costs in the years ahead.

4. Some relevant technology trends

4.1. Ecological adaptation

4.1.1. The basic principle

An ecological approach is useful for examining what otherwise may stir emotions around personal stakes. Among other, ecology addresses the established position of an incumbent in a particular system vis-à-vis the extent to which another player can enter and participate. The interaction thereafter may be predatory, or symbiotic, or both. In major railway technology issues, there tend to be two major contenders, as in the present paper, although ecology does generalize to any number of contenders. Their relative strengths and weakness are obviously important. However, the cost of switching may protect an incumbent, and the order of appearance of contenders may ultimately prove to be more decisive than their relative merits.

4.1.2. An illustration of ecology

Electric traction started to challenge the dominance of steam traction in the 1890s (Barker & Robbins, 1975: 310), and by the 1920s had established itself in particular niches. The internal combustion engine of that time was not competitive with either electric- or steam traction. Several decades of development were to pass before diesel locomotives capable of challenging both electric- and the remaining steam traction appeared. Manufacturers and railways realized early on that electricity was a clean, quiet and powerful alternative to steam locomotives. However, the large investment in infrastructure precluded electrification from all but a few applications (Coifman, 1994).

Electric traction is rooted in situations where steam traction performed poorly, such as long tunnels and/or steeply graded routes. It has subsequently thrived where dense, well-defined, stable traffic flows exist. Densely trafficked passenger corridors, such as city rail and high-speed intercity railways, plus a few heavy haul railways, currently meet the latter condition.

By the end of World War II diesel locomotives had developed sufficiently to challenge the dominance of steam traction in mainline freight service in North America (Coifman, 1994). They toppled steam by being able to haul heavier loads faster at lower cost. Diesel traction currently thrives where the cost of electrification infrastructure is inordinately high. This occurs in niches where traffic flow is sparse, variable from load to load, and subject to market vagaries, or where track layout is complex, such as in yards.

Steam traction was thus displaced, at different times and for different reasons, by two diverse contenders, namely electric- and diesel traction. In turn, they now contend the global traction market. The two motive power types may also be symbiotic: Electrically dominant railways frequently deploy diesel traction in situations where the complexity of electrification infrastructure, or the sparseness of traffic, renders electrification unjustifiable, or where they require an uninterruptible power supply.

4.1.3. Prognosis

Motive power contention has by no means achieved a stable outcome yet. The lower tolerance for deviation from a set timetable in passenger service, together with relatively light loads and higher frequencies, yields better diversity than the concentration of tonnage or trains that may occur in freight service. Regarding their relative strengths, electric traction seems more at ease with passenger operations, whereas diesel traction seems more at ease with freight operations.

The cost of electric energy versus diesel fuel has of course always been an important discriminant, as has capital cost. However, when external energy supply infrastructure is already in place, the choice of new locomotives gravitates to the apparently low variable cost of energy. Thus, order of appearance only allows diesel locomotives, which have advanced significantly in recent years, to penetrate slowly in traditionally electrified markets. When external energy supply infrastructure is not in place, the choice of new locomotives tends to gravitate to the risk of investing in such infrastructure. The cost of switching cost has apparently deterred electrification in traditionally diesel markets.

One should thus expect the course of further ecological adaptation to follow on this pattern. This paper explores one way to facilitate that adaptation.

4.2. AC traction motors and DC link voltages

In recent years, there has been a shift to alternating current traction motors for new locomotives. Such motors may accept higher supply voltages than the direct current motors they superseded. Furthermore, the voltage (and power) rating of electronic devices has been steadily increasing. Older GTO technology already accepts 3kV direct current overhead supplies. IGBTs able to operate at this level, but on a smooth supply, are imminent. EMD's forthcoming SD89 diesel locomotive, for example, will have a 2.8kV direct current link between rectifier and inverter. This is significantly higher than the 600-1000V motor voltage common some years ago, and in the 3kV direct current electrification ballpark.

It has now become feasible to conceive of a locomotive with the ability to use different energy sources, either diesel fuel or electricity, over different route sectors. It would probably be a mass-produced diesel locomotive, equipped additionally with a pantograph, circuit breaker, and filter. On sectors so provided, the direct current contact wire would feed directly into the rectifier-inverter link, thereby avoiding the cost of diesel fuel. On sectors without external supply, the locomotive would function as a conventional diesel locomotive.

It would thus be feasible to electrify selectively (to avoid the cost of providing new infrastructure), or to de-electrify selectively (to avoid the cost of maintaining existing infrastructure), as the case may be. Of course, electric braking would be rheostatic only: Vide Paragraph 2.2.2, this should not be a loss. For want of an accepted term, the author will use *electric assist*. The next section examines what topographical conditions may favour electric assist.

5. A logistics view on traction energy distribution

5.1. The essential issue

The author argues that the essence of the material presented thus far is applying a source of energy to power the traction motors of a locomotive. In a technology classification sense, the issue encompasses the processing, transporting and storing of energy (Van Wyk, 1991). This is the essence of logistics, which is a useful perspective from which to approach the rest of the paper.

5.2. Topographic analysis

5.2.1. Nature of traction

Freight trains use full power on most, even light, ascending grades. Hence, they normally need a substantial energy supply over specific, concentrated, portions of a route only. They either coast or brake over the rest of the route. The author examined computer simulations of energy consumed by typical trains, on a distance base, using Spoornet’s standard freight train driving techniques, to identify sections that seemed suitable for electric traction. The following criteria seemed appropriate:

> Include at least one kilometer at full power operation. Such short sections are few—most are considerably longer than one kilometer.
>
> Apply- and shut down power at points of no load. Many sections include a ramp-up or ramp-down portion at one or both ends.

The relative proportions of motoring, coasting and braking depend on a variety of factors. They are best illustrated by Pareto analysis of the energy used according to the above criteria on the following three routes (note that passenger trains are insignificant in Spoornet’s traffic mix).

5.2.2. The Johannesburg-Durban mainline

This 700km double-track route, electrified at 3kV direct current, follows a relatively old alignment. This, Spoornet’s most important non-heavy-haul operation, was upgraded piecemeal, the current rendition dating from the 1950s to the 1980s. The Pareto diagram in Figure 3 shows that approximately 90% of the energy is consumed over some 40% of the distance. Evidently, there is scope to restructure energy distribution. Paragraph 5.3 addresses this issue.

5.2.3. The Sishen-Saldanha iron-ore export line

This 861km single-track route, electrified at 50kV alternating current, was commissioned in 1976 as a dedicated heavy haul line, through relatively easy terrain that permitted 0.4% ascending- and 1% descending grades, in the loaded direction. The Pareto diagram in Figure 4 shows that energy is consumed more uniformly over the distance than on the Johannesburg-Durban route, particularly in the empty direction. The relatively greater role that rolling resistance plays on flatter grades would account therefor in part. In this sense, the route seems akin to a high-speed passenger route, where aerodynamic drag accounts for a relatively high proportion of total resistance. Being a single line, there is thus probably not much scope to selectively de-electrify, because some 82% of the route would need to remain electrified. Furthermore, it would require new locomotives to be equipped with transformers and rectifiers, which would be impractical if not uneconomical. This examination confirms that the existing design is effective.

5.2.4. The Ermelo-Richards Bay coal export line

This 420km double-track route, electrified at 25kV alternating current, was commissioned in 1976 as a dedicated heavy haul line, through mainly rugged terrain on 1.52% ascending- and descending grades. It was extensively upgraded in the late 1980s, at which time the ascending grades were eased to 0.625%. The Pareto diagram in Figure 5 shows that in the loaded direction some 87% of the energy is consumed over only 27% of the distance. There may be scope to apply electric assist in this direction. By contrast, in the empty direction 95% of the energy is consumed over 72% of the distance, much more uniformly than in the loaded direction. Although some 50% of the combined up-and-down route length could be de-electrified, the alternating current supply would require new locomotives to be equipped with transformers and rectifiers, which would be impractical if not uneconomical. The author did not analyse this route further.

5.3. Relative cost analysis

Using the Johannesburg-Durban mainline as a role model from which to generalize, Table 1 analyzes the influence of the following factors:

> *Electrification of 100% of distance* and supplying 100% of energy consumed (i.e. conventional electrification), versus *electrification of 40% of distance* and supplying 90% of energy consumed (i.e. the remaining 10% being supplied by a diesel engine).
>
> *Traffic volume*.
>
> *Capital cost of locomotives*—ZAR15 000 000 for diesels and ZAR22 000 000 for electrics.
>
> *Diesel fuel and electric energy prices*.
>
> *Substation spacing*: Spoornet’s practice is to space them at approximately 12km intervals for a direct current supply. The model simply calculates how many such 12km sections will be required, and computes the appropriate capital and operating costs.
>
> *Fuel tax rate*.

The analysis uses average Spoornet values. Precise data are notoriously elusive, so one should regard the present analysis as a first cut, to assess whether further research is justified or not.

The outcome shows that electric assist can match conventional electrification in comparable cost. It also shows that, in South Africa, the choice between diesel- and electric traction is sensitive to the diesel fuel tax rate. The analysis is not sufficiently precise to suggest an investment strategy: The outcome is however so close that one should examine future investment decisions carefully. It also does not include the economic advantages of a completely interoperable locomotive fleet mentioned in Paragraph 5.7.

5.4. A role for electrification?

5.4.1. What voltage?

The author’s reasoning is predicated on supplying locomotives at approximately 3kV direct current. This voltage is no longer favoured for new electrification, but it does relate to the direct current link voltage on locomotives equipped with alternating current traction motors. Spoornet provides traction power at this voltage to multiple-locomotive consists in the 8-12MW range, which has proven to be an acceptable rating for general freight trains and entry-level heavy haul trains.

The foregoing reasoning calls into question the role of alternating current electrification. In the light of the present analysis, its eminent domain seems to encompass dedicated routes with relatively uniformly distributed energy consumption, with frequent, high-power services. Furthermore, an alternating current supply requires a transformer and rectifier per locomotive to supply its direct current link. Aside from cost, it may be difficult to accommodate them within the size and mass constraints when there is a diesel engine and fuel tank to start with.

Depending of course on the amount of traffic, electric assist only needs transformers and rectifiers at electrified sites, probably fewer in number than would be required to provide equivalent equipment on all locomotives.

5.4.2. Reducing the risk

It is now realistic to reassess the essence of electrification in traction energy distribution. Need it be more than intermittent, at sites where the delivered price of electricity is less than the price of the fuel (in the tank of the locomotive) that would otherwise have been consumed?

A high proportion (as much as 90% in this analysis) of total energy may be consumed on long upgrades. Around the world, they are typically 10-35km in length, requiring from one to three substations. The remaining energy consumption spreads thinly over the undulating terrain or descending grades in between. It is thus possible to define precisely the sites at which electric energy may offer economic advantage over diesel fuel.

Electric assist would minimize business risk through minimizing the amount of, and hence investment in, electrification infrastructure.

5.5. Possible system configurations

5.5.1. Present feasibility

Technology has advanced to a stage where it is opportune to explore convergence of both diesel- and electric traction on the same locomotive. Diesel traction offers robustness, versatility, relatively low capital cost, and low risk. Electric traction offers low operating cost at sites where trains demand high power over relatively short distances. The notion presented here, namely selective electrification or de-electrification, provides the key to converging these advantages. Some relevant concepts are already well established, for example:

> In Southern Africa, Iscor, Palabora Mining Company, and Rössing Mine operate haul trucks that exemplify the concept well. They are conventional diesel powered vehicles, but fitted with aftermarket conversions that draw energy from direct current overhead contact wires on the ramp out of the open cast mine. The first generation design, applied to trucks with direct current traction motors, was an elementary solution that applied the external supply directly to the wheel motors. The limitations of not being able to start from rest, and not being able to control speed, would however not work for a railway.
>
> Spoornet’s Class 38 locomotive (and similar locomotives elsewhere), although not so intended, represents a conceptual halfway station. At 750kW, its diesel engine is relatively small, but under 3kV direct current catenary it puts out 1500kW. It was acquired to haul traffic to and from major yards, where the ability to operate on non-electrified private sidings and branch lines is valuable, as is the ability to run economically and speedily under wire.

For the future, two options come to mind—use existing infrastructure and apply electric assist to new locomotive purchases, or start from scratch with new selective electrification infrastructure to supply new locomotives. Electric assist may be viable in areas already served by a national grid, but will probably not be viable in areas that need an extension specifically for traction purposes.

5.5.2. Issues for research

Three electricity supply options present themselves. First, where there is no need to run double-stack container trains, standard-height catenary is appropriate. Second, where double stacking is essential, extra-high-clearance catenary may offer a solution. Third, where neither of the previous options is feasible, third rail may offer a solution.

These options need further research in the following three fields.

> Pantograph hookups are not unknown: Automatic raising and lowering of pantographs in motion would probably be essential.
>
> The dynamic behaviour of extra-high-clearance catenary is uncharted territory.
>
> Intermittent catenary with in-motion pantograph raising and lowering may be less attractive than intermittent third rail. Three-kilovolt third rail is not current practice, but neither has it

benefited from free market competition. Cortie (2000) has suggested that third and fourth rail at plus and minus 1.5 kV could give 3kV within the bounds of current third rail practice.

5.6. Energy- and fuel outsourcing

5.6.1. Electric energy

Electric assist offers an opportunity to introduce competition into the supply of energy to specific trains, rather than to whole railways. Because the physical extent of external electricity supply is limited and clearly defined, it is feasible to outsource this function to the electricity supplier. Current thinking in supply chain management would also allocate electrification infrastructure ownership to the energy supplier, rather than to the track owner. Transponders could establish a one-to-one relation between user and consumption on electrified sections, to bill operators accurately. This would facilitate open access regarding a function that is problematic for an open network.

5.6.2. Diesel fuel

Current Spoornet practice, and that of many other railways, is to receive diesel fuel in bulk tanks at locomotive depots, from which it is dispensed to individual locomotives. Electric assist would reduce the fuel used per trip, thus permitting either a longer refuel span, or a more powerful diesel engine but smaller fuel tank within a given axle load limit. Technology to optimize use of a tank of fuel is already commercially available.

Spoornet does not refuel locomotives either on main lines or from road tankers. Such refueling processes can obviously shorten turnaround time and/or reduce infrastructure requirements. Clearly electric assist also offers scope for achieving a lean diesel fuel supply chain.

5.7. Peripheral issues: A new mindset

At present, only diesel traction offers freight railways complete interoperability among all locomotives. Electric traction cannot support a freight railway without a modicum of diesel assistance: Such a railway can never enjoy the simplicity of a single type of motive power. Electric assist offers the possibility of eliminating many of the costs associated with owning or operating both diesel and electric locomotives. It changes a railway’s mindset, from electric plus diesel, to diesel only (but with an outsourced energy supply competitor). The following are some economic advantages that accrue to a single type of motive power:

Avoid electrification of complex layouts, such as yards.
Avoid electrification of lightly trafficked but essential links.
Avoid changeover facilities from diesel- to electric motive power and vice versa.
Avoid changing motive power en route, and facilitate unit trains running siding-to-siding.
Avoid an undue multiplicity of locomotive classes.
Avoid maintaining an undue variety of locomotives.
Avoid delaying trains while changing motive power.
Avoid poor crew utilization when changing motive power.
Avoid brake tests when changing motive power.
Avoid standby locomotives and crews for overhead traction equipment maintenance.
Avoid standby locomotives and crews for overhead power outages.
Avoid delays due to complete or partial loss of electricity supply.
Avoid line losses over sectors currently electrified but not in Pareto 80-90% subset.
Avoid direct current to alternating current changeover yards.
Avoid training drivers on different types of motive power.
Avoid frequent refueling.

6. Conclusion: Getting the best of both worlds

Electric assist is predicated on exploiting a trade-off between lower capital cost of diesel locomotives and possibly higher cost of energy. It challenges the mindset that an electric railway needs to be totally electrified. Indeed, it seems feasible that a freight railway can enjoy the low price of electric energy together with the flexibility of diesel traction. In South Africa, with an established 3kV direct current freight network, that needs to renew its locomotive fleet, the relatively low capital cost of standard diesel locomotives, plus the low cost of electric energy, may constitute a formidable package.

From Figures 1 and 2, South Africa has the lowest electric energy price in the world, but occupies the 38th percentile of the present sample regarding diesel fuel price. Even at this nexus, the analysis finds the value of electric assist to be marginal, but sensitive to the tax rate on diesel fuel. In this situation, the decisive benefit would reside in the simplicity and flexibility of a single type of motive power. Elsewhere in world, where the relative diesel fuel- and electric energy prices more favourably related, one may expect a strong case for electric assist.

Electric assist could introduce and stimulate competition between both sources—diesel fuel and electric energy—that is ineffective at present. The ultimate outcome would depend on the ecological structure of the market in which they compete. Prima facie, there appears to be a need for more thorough analysis.

Fuel cell technology is still a wild card, and it is not within the scope of this paper. However, from an ecological perspective, one would expect such a new technology to affect diesel locomotives first, simply because they are relatively smaller than large power plants supplying a national grid. In addition, again from an ecological point of view, one would expect fuel cell locomotives to be more competitive, against electric locomotives, than diesel locomotives. Electric assist may therefore be an elegant migration path through selective de-electrification to ultimate complete de-electrification.

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