OPTIMISATION OF THE ECONOMIC RELATIONSHIP BETWEEN TRAIN HANDLING AND TRACK MAINTENANCE

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ABSTRACT

Train handling techniques influence the way locomotives exert tractive and braking forces and hence track loading in the longitudinal direction. On the Ermelo-Richards Bay line longitudinal distress of the track structure offered evidence of abnormally high longitudinal forces, which led to the investigation described in this paper.

The relationship between longitudinal forces exerted by locomotives and track maintenance costs has been established empirically. Energy which has been consumed by locomotives may seep into the track structure via wheel/rail contact and be dissipated by increased track disturbance and accelerated wheel/rail wear. Factors such as application distance of traction and braking forces, energy consumption, energy transfer speed, vehicle stability, train speed profile, superelevation and driver skills influence the relationship. Energy saving train handling techniques minimize energy seepage from train to track structure because less superfluous energy is available for degradation. Balancing the factors described herein can significantly reduce the demands which locomotives make on the track structure.

Heavy haul and general freight railways operate in markets which demand increased operating speed, axle load and train length. Advancing technology has enabled the rating of power electronics and traction motors to keep pace with these demands. Higher dynamic brake ratings are also becoming more widely accepted. Investigation into train handling characteristics expected from future generations of locomotives has indeed revealed the ratio of rated power to tractive/braking effort to be a key criterion. Such an environment increases the amount of energy which may potentially be input into trains. The amount of energy actually consumed is however a function of the situational parameters and of the train driver's skill, both of which therefore require careful management. Computer simulation models tuned to actual driving practices are a useful management tool in this regard.

It is concluded that train handling techniques and hence energy consumption are a significant determinant of longitudinal track loading and hence of related track maintenance costs. Correct management simultaneously reduces both energy consumption and track maintenance. Energy efficiency then becomes a useful yardstick with which to determine the state of health of a railway operation.

1 INTRODUCTION

Train handling is an art because human perception and interpretation play significant roles, despite a scientific foundation. Train handling influences the way locomotives exert their tractive and braking forces. The latter are exerted in the longitudinal direction only and phenomena in other directions will be disregarded. This paper expands on issues previously presented by the author (1990). The theoretical ground will be cursorily reviewed herein, after which the economic relationship between train handling and track maintenance will be addressed.

Whilst the capital cost of a project is fixed at commitment, post commissioning operation is required to provide acceptable returns despite unforeseen difficulties. This paper offers insight into some techniques which Spoornet has used to manage post investment returns. For the purpose of this paper only, heavy haul operational costs are characterised by two elements, energy costs and maintenance costs.

This paper presents insights gained during train dynamics research and development on Spoornet's Ermelo-Richards Bay line. It conveys predominantly coal over 410km from the Transvaal coal fields to Richards Bay on the East coast. Key statistics will be compared with those of the Sishen-Saldanha line, which conveys iron ore over 860km from Northwest Cape mines to Saldanha Bay on the West coast. Figure 1 is a map showing these lines.

The Ermelo-Richards Bay line was upgraded during the 1980's to accommodate cars of 26 tonnes (28,7 short tons) per axle and locomotives of 28 tonnes (30,9 short tons) per axle. Suitable new cars and locomotives were commissioned concurrently. Amongst other, 60 kg/m (121 lb/yd) Cr-Mn rail replaced the original UIC-A rail. At that time loads of 136-176 cars were worked by three head end plus five mid-train electric locomotives. Despite coupler forces rising due to growth of trailing loads, no abnormal locomotive wheel flange wear was encountered until the Cr-Mn rail was laid. When abnormal wear emerged thereafter, it was inferred that the angle of attack of non-self-steering locomotive trucks under traction was being increased by abnormally high tractive efforts. Subsequently, longitudinal distress of the track structure, mainly on ascending grades against loaded trains, provided further evidence of abnormally high longitudinal forces. When 200 car, 20800 tonne (22920 short tons) trains were introduced in February 1989, advanced energy saving train handling techniques were simultaneously introduced. Although reduced energy consumption and lower train action forces were sought, significant interrelationships between train handling and longitudinal locomotive/track interaction were also discovered.

2 ENVIRONMENTAL INFLUENCES ON TRAIN HANDLING

2.1 Market and system trends

Competition in heavy haul and general freight markets increases operating speed, axle load and length of trains. In the context of this paper, the essential consequences are escalating gross train tonnage and escalating aggregate locomotive consist tractive/braking effort. Aggregate energy consumption per consist may consequently also increase, subject to the capacity constraint of the source and the extent to which higher speed per se is economically attractive. Beyond the limit of permissible coupler strength, further tonnage cannot be handled by a single head end locomotive consist and an additional remote locomotive consist may then be required. This increases the complexity of the issues raised in this paper.

2.2 Fluency in train handling

Investigation into train handling characteristics expected from future generations of locomotives has revealed the kW/kN ratio in both traction and braking to be a key criterion. This is because train handling set up dominates fluency and hence train drivers' practical implementation of their training. The units of this ratio are force x distance x time^{-1} x force^{-1}, which yields speed. It is a useful conceptual tool for comparing locomotives with disparate adhesion and axle load combinations. In traction, this ratio gives the balancing speed, but there is not a commonly accepted equivalent term in braking. This speed is that up to which tractive/braking effort exceeds the resultant of grade force and rolling resistance. Up to this speed, actual tractive or braking forces are at the train driver's discretion rather than being dictated by motor rating. Subjectively, the higher the kW/kN ratio, the more fluently a train can be handled. This in turn allows a driver greater latitude as to where he imparts energy to a train. A rather crude index of handleability is obtained by simply adding together the pair of kW/kN ratios for a locomotive, as in Figure 2, which compares selected North American locomotives with selected Spoornet locomotives. Spoornet's developmental thrust is clear.

2.3 Advancing technology

Advancing technology has steadily increased the rating of power electronics and traction motors. Particularly in electric traction, availability of 2MW inverters makes the 5MW (6700HP) locomotive an attractive proposition, even on gauges as narrow as Spoornet's 1065mm (3'-6"). Hence the amount of energy which may potentially be input into a train is increased. The amount of energy actually consumed is however a function both of the situational parameters and of the train driver's skill. Figure 3 shows the result of simulating the relationship between locomotive power rating and energy consumption as a function of trailing load for constant train handling techniques and locomotive axle load on selected lines. It is evident that theoretical energy consumption is relatively insensitive to the power to tractive effort, or kW/kN ratio. The sensitivity is typically less than 1% increase in energy consumption per 10% increase in kW/kN ratio over a wide range of topography. This enhances the attraction of three phase asynchronous traction motors, particularly where the characteristics of heavy haul and general freight locomotives potentially overlap. This paper will raise issues relating to the trade-off between handling fluency and risk of increased maintenance.

2.4 Acceptance of higher dynamic brake ratings

Higher dynamic brake ratings facilitate higher speeds through sags and encourage train drivers to extend their planning horizon, often from crest to crest without motoring in between. This technique applies forces between locomotive and track at relatively high speed, thereby minimizing use of the low speed, high effort portion of locomotives' characteristic curves. It also enables locomotives to be used more in the electric braking mode, where maximum braking effort is deliberately restricted, and less in the essentially unrestricted traction mode. Higher dynamic brake ratings are normally available only on new locomotives. However, Spoornet is presently upgrading the dynamic brake on a series of 50 electric locomotives from 1.7MW (2300HP) to the full traction motor rating of 3MW (4000HP), to handle heavy haul traffic growth. Spoornet uses heavy haul locomotives with dynamic brake ratings of 4500 kW (6000 HP) and is investigating characteristics for future mainline heavy haul/general freight locomotives with dynamic brake ratings of up to 5000kW (6700HP). This requires adequate track standards, chiefly well secured rails to resist lateral forces and turnouts without gaps into which the wheel flanges can enter. Quality of track structure must be balanced against energy saving train handling techniques.

3 ENERGY CONSUMPTION AND DISSIPATION BY TRAINS

3.1 Minimum and superfluous energy

The concepts of minimum and superfluous energy have previously been introduced (Van der Meulen 1990). Briefly, the theoretical minimum quantity of energy to move a train is determined by integrating the total resistance to motion over the profile traversed, plus or minus any net kinetic energy change. In practice, energy consumption may significantly exceed this theoretical minimum value. Local topography influences both theoretical and actual energy consumption. This is illustrated by computer simulated return trip energy consumption of respectively 9,0 and 6,3Watt-hours/tonne-km on Spoornet's Ermelo-Richards Bay and Sishen-Saldanha heavy haul lines, for comparable 200-210 car trains grossing 21┼000-22 000 tonnes (23 000-24 000 short tons). See Figure 3 once again. The former line traverses relatively rugged terrain, while the latter traverses more easy desert terrain. The efficiency with which motoring, braking and train action are managed determine the actual energy consumption. The corresponding values for financial year 1990 are respectively 9,5 and 8,8 Watt-hours/tonne-km, which yields efficiencies of 95% and 71%. The Ermelo-Richards Bay operation has been subjected to intensive development, which is currently being extended to Sishen-Saldanha. The value of this effort speaks for itself. During the period under review no meaningful changes have been made to locomotive or power transmission technology on these lines and therefore energy conversion efficiency is not relevant.

3.2 Superfluous energy dissipation on Ermelo-Richards Bay line

After refining train handling fully within conventional practice, Spoornet found that further energy saving was accessible through understanding longitudinal locomotive/track interaction. The phenomena noted in paragraph 1 prompt the question of what previously happened to superfluous energy saved through improved train handling. Energy consumed in excess of the theoretical minimum must inevitably be dissipated. By the rudimentary criterion that it causes abnormal damage or financial haemorrhage, such dissipation may be termed significant or insignificant. The following dissipaters are considered insignificant in the context of this paper:

Errant train handling techniques, such as power braking and tardy anticipation, which dissipate superfluous energy via tread braking. On the subject line these are considered insignificant because, since inauguration, composition brake block life of 240 000km (150 000 miles) has consistently been achieved, despite increasing axle load from 18- to 26 tonnes (20.4 to 28.7 short tons) and average speed from 37 to 48km/h (23 to 30 mph).

Train action dissipates energy in drawgears. However, because coupler forces are extremely high, dynamic augment must be kept extremely low. Drawgears are repaired after six years' service. When related to turnaround time and haul length, this equates to

±50 years' normal service, which indicates that train action does not dissipate significant superfluous energy.

Car flange/rail contact may dissipate significant amounts of energy. Lubrication of the contact zone has reduced energy consumption on many railways, but the procedure is not applicable to cars equipped with self-steering trucks because flange/rail contact is negligible.

Significant degradation of superfluous energy on the subject line took two forms. The first was severe longitudinal distress of the track structure. In retrospect, it has become clear that track structure can dissipate enormous quantities of energy before it is noticeable that something is amiss. The second was wheel flange wear on locomotives, all equipped with non-self-steering trucks, some four to five times faster than normal, accompanied by accelerated wear on the high leg gauge face in curves. Such energy degradation is insidious, because the evidence only emerges after a protracted time, when the damage is well established.

4 DETERMINANTS OF LONGITUDINAL TRACK FORCES

4.1 Locomotive mass and power

Spoornet's heavy haul cars employ self-steering trucks which minimize rolling resistance by avoiding flange contact. Forces exerted by cars on the track are therefore predominantly in the vertical direction. The heavy, concentrated longitudinal forces which are the subject of this paper are applied by locomotive consists. Although non-self-steering locomotive trucks may exert significant lateral forces, in train handling terms this is a second order effect. Locomotive traction and dynamic braking characteristics with respect to speed are therefore germane to longitudinal track loading. It is important to distinguish between mass and power, because each has its own contribution to longitudinal forces. In principle, mass determines the magnitude of force a locomotive can exert, whilst power determines the speed at which a force can be exerted. Lack of appreciation of this distinction may cause confusion regarding the longitudinal forces which locomotives exert on track.

4.2 Tractive effort/speed characteristics

The essentially hyperbolic tractive effort/speed characteristic of locomotives allows exertion of high tractive effort at low speed. Ultimate tractive effort is limited by incipient wheelslip at the adhesion limit. Under favorable conditions 30-40% is attainable, which allows extremely high tractive efforts from large locomotive consists. On ascending grades, diesel-electric locomotive consists balance at a speed which is independent of the number of locomotives in the consist. However, in the case of straight electric locomotives, substation capacity and catenary voltage drop mean that the power available to a consist is not altogether independent of the number of locomotives in the consist. When drivers reduce demand to avoid tripping substations, the locomotives operate on a reduced power curve. They may then operate within that portion of their characteristic tractive effort envelope which is higher than the tractive effort at normal balancing speed and therefore normally inaccessible. This condition is aggravated when load sharing between multiple consists is disturbed by reducing tractive effort at the lead consist for fear of coupler failure, whilst simultaneously increasing tractive effort at the in-train consist so that it takes more than its share of the load because the risk of coupler failure there is smaller.

4.3 Dynamic braking characteristics

Powerful dynamic braking facilitates fluent handling of heavy trains. When used to dissipate energy at constant speed on long descending grades, as distinct from braking reliably to stop at the end of a movement authority, adhesion demand relatively higher than in traction can be tolerated. When there is no risk of overturning the rail or wheels entering gaps in it, such as when cars with self-steering trucks operate on continuous welded rail on concrete sleepers, higher compressive coupler forces are acceptable. Under such conditions Spoornet applies quasi-static dynamic braking forces of up to 1450 kN (330 000 lb force) to the rail. In respect of longitudinal track loading there is thus practically no significant difference between maximum quasi-static tractive and braking forces, because the locomotives of a heavy train exert high longitudinal forces on both ascending and descending grades.

5 HOW COUPLER FORCES INFLUENCE TRACK FORCES

5.1 Maximum sustainable coupler force

During the late 1970's and early 1980's, market growth on the Ermelo-Richards Bay line was accommodated by heavier trailing loads hauled by larger locomotive consists. Simultaneously, advancing traction technology raised usable adhesion from ±18% on export model diesel locomotives to ±24% on high-tech straight electric locomotives. Study of the parameters which determine train action by means of fully instrumented trains ultimately enabled train drivers to be trained to realise the full coupler force potential by minimising dynamic train action. Quasi-static forces of 1500-1600kN (340-370 000lb force) have been found workable with E/F-type couplers without unduly increasing the risk of coupler failure through harsh train action. Advanced train handling techniques using heavy, high adhesion, expertly handled head end locomotive consists thus apply tractive efforts to the track structure which may attain critical values.

5.2 Tractive efforts inherently limited

Longitudinal forces applied by locomotives to the track are a function of sustainable coupler forces. Ultimate coupler strength is therefore a "safety valve" for the aggregate tractive effort of a head end locomotive consist. In-train consists distribute their total tractive effort between two couplers. This counteracts the safety valve and allows in-train consists to apply extremely high longitudinal forces to the track. Spoornet has measured forces of the order of 2000kN (450 000lb force), applied over the length of an in-train consist of five locomotives. Such forces are large enough to distress the track structure.

5.3 Rail breaks and kick outs

Longitudinal forces applied to the track by locomotives oppose gravity and are therefore always in the same direction, independent of direction of motion and independent of whether traction or dynamic braking is applied. The resulting tendency of the rail to move is therefore always away from a crest towards a sag. Spoornet's 1990 total rail break and kickout occurrences, which led to derailments, have been related to the position of crests and sags in Figure 4. Rail stresses are carefully managed and thus kickouts are relatively rare. Generally, rail breaks occur near a crest and kickouts occur near a sag. This suggests that rail breaks and kickouts are influenced by longitudinal forces applied by locomotives, and could therefore be minimized by energy saving driving techniques.

6 TRAIN HANDLING IMPACT ON TRACK MAINTENANCE ECONOMICS

6.1 Relevance of train handling

The foregoing issues indicate that locomotive/track interaction is an important contributor to track maintenance costs. Spoornet's advanced, energy saving handling for heavy haul trains originally was targeted at reliable train operation. However, it was soon found that attention to the issues described in this section significantly reduces the demands which locomotives make on track. The relationships between longitudinal forces exerted by locomotives and track maintenance have been established empirically within Spoornet, but as yet there is not a full understanding thereof. In principle it is desirable to transfer the maximum possible kinetic and potential energy from a descending grade to the next ascending grade by applying elementary physics. This minimizes the amount of energy seepage from train to track because there is less superfluous energy which can be dissipated by increased track disturbance and accelerated wheel/rail wear. From a track point of view, both the forces and amount of energy which tend to move the track downgrade are reduced. Although track lubrication in curves had ameliorated the locomotive wheel flange wear problem on the Ermelo-Richards Bay line, the wear rate only stabilised at its original value after energy saving driving techniques had been implemented. To optimise heavy haul services, as many as possible of the following items should be considered:

6.2 Application distance of traction and braking forces

Maximum quasi-static tractive and braking forces are determined by the steepness of a grade and the mass of a train. On long grades these forces are therefore essentially independent of driving technique. Spoornet's train drivers are taught to think of energy consumption or dissipation as force multiplied by distance. Although maximum quasi-static forces are usually not under their control, they can significantly influence the distances over which they are applied. Energy saving driving techniques therefore reduce the distances over which high forces are applied, in many instances eliminating high forces at balancing speed on grades of 5km and longer. High kW/kN enables useful tractive effort to be applied at higher speed and so reduce speed loss on ascending grades. This means that balancing speed and maximum tractive effort may only be reached 10km or more after a sag. Practical implementation is facilitated by impressing on train drivers that gravity should not be resisted more than is consistent with the train handling practices they are taught, as this ultimately leads to applying traction and braking forces over longer distances and hence to dissipation of superfluous energy.

6.3 Energy consumption

Minimizing the energy input into a train minimizes the superfluous energy which can subsequently be wastefully dissipated by damaging track. Inherently low energy consumption may in the first instance be effected by increasing train length as far as practicable within physical and commercial constraints. This reduces external energy requirements by transferring potential energy via coupler forces internally within the train in certain circumstances. Management of train action ultimately limits the gain from this technique in heavy haul service. Thereafter, train drivers must consume energy frugally by conserving that which they have already imparted to a train. They must conceive of use of throttle or accelerating lever as imparting a quantum of energy to a train, with the intent of applying that energy to attain a specific topographical objective. Similarly, they must appreciate that use of dynamic braking removes a quantum of energy from a train and degrades it to a useless form, unless regenerative braking is available and effective. Spoornet teaches drivers to regard the train itself as a temporary store with which to transfer kinetic energy from where it is not required to where it will be required. Of course, this concept outlaws power braking.

6.4 Energy transfer speed

Energy should be imparted to or removed from a train at the highest practical speed, so as to operate locomotives at the lowest practical tractive or braking effort and hence minimize longitudinal forces applied to the track. Energy may be imparted at a favorable locality and transferred within the train for application at some other locality where train handling might otherwise be more awkward. In certain low speed situations drivers may thus be able to deliberately reduce tractive effort to avoid overloading couplers and hence also application of high └ longitudinal forces to the track. The amount of kinetic energy transferred across a sag is a function of speed squared. It is therefore important to avoid restricted speeds or hindrances in sags such as substandard lineside signal braking distances and placement of turnouts where train speed is naturally relatively high. Impeding energy transfer within trains only encourages application of higher tractive and braking efforts elsewhere.

6.6 Vehicle running stability

Stable trucks on locomotives and cars are important to the energy saving philosophy expounded herein. When instability sets in, lateral forces may become harmful before train speed is high enough to transfer useful amounts of energy across a sag. Instability may increase the track maintenance cost and may reduce, nullify or negate any energy saving. If trucks are stable up to any speed within the spectrum of feasible train handling, energy transfer across sags may be optimised because there is only saving, with no trade-off against possibly increased maintenance. Also, take into account that drivers occasionally exceed maximum authorized speeds.

6.7 Train speed profile.

Application of energy saving driving techniques over grade changes is characterised by relatively large speed variation over the length of a train. Because the train itself is used to transfer energy, the range of speed variation between front and rear whilst passing a given point may widen due to conversion of potential energy to kinetic energy and vice versa. The range of speed variation is also a function of train length, because train length increases the sum of the preceding and following components of the moving average speed at a particular point. Although the speed variation can be surprisingly large through sags, minimizing energy consumption nevertheless also minimizes slack action and dynamic coupler forces. For the 2500m trains currently operating on the Ermelo-Richards Bay line, the minimum speed in a sag is typically 60% of the maximum speed at that same point, with a standard deviation of 10%. This compares favorably with 30-80km/h swings when these trains were first introduced in February 1989. The speed variation over a crest is typically much smaller, because it is approached from an ascending grade on which speed is already limited by locomotive power and/or catenary capacity, and the speed on the next descending grade could be limited by thermal capacity of car wheels. For this reason the speed variation over a crest is typically well under 10km/h. However, where a ruling ascending grade is followed by a ruling descending grade over a minimum vertical curve, drivers may sacrifice some kinetic energy to reduce coupler forces at the front of the train, in which case the speed variation may increase to around 20km/h.

6.8 Superelevation

The resulting wide band train speed profile makes it difficult to optimise superelevation so as to minimize track maintenance. In heavy haul service, as distinct from mixed traffic, the nominal speed profile is known and track maintenance resources may therefore be directed appropriately. Unavoidable excursions from the natural speed profile, such as temporary speed restrictions, maximum demand control, low catenary voltage and traffic congestion may compound this problem. Spoornet's investigation into resolving this conflict has focused initially on train handling to minimize the speed band at any particular point. An awareness of the problem and greater familiarity amongst drivers has already accomplished an improvement of roughly 50% in the ratio of minimum speed to maximum speed at any particular point. Unavoidable excursions at this time remain a problem. In new construction, it is desirable to reduce sensitivity to superelevation by avoiding tighter curves where high speed variation is expected. Spoornet is currently using computer simulation to identify locations where economic potential for easing particular sags exists.

6.9 Enhance driver skills

From the foregoing discussion, reduced energy consumption and hence reduced longitudinal influence of trains on track, entails longer trains, heavier trains, higher average speeds and larger speed variations over grade changes. These parameters strain accepted boundaries and therefore require to be securely managed to maintain adequate safety levels. The whole package forms an integrated whole which must be brought together by the train driver. This places new demands on selection, training and maintenance. Higher speeds must be used responsibly. Handling large speed variations without harsh train action which could negate the benefits demands high skills. Train drivers must be sensitized to the influence of train handling on the energy they consume.

6.10 Two vignettes

The Ermelo-Richards Bay line: Energy consumption expressed in Watt-hours/gross tonne-km decreased by some 40% during the period under consideration, as shown in Figure 5. This saving was achieved by increasing train length, reverting to head end locomotive consists and refining train handling. The correlation with locomotive wheel life is also clear. Research has been undertaken to locate sites where major amounts of energy are imparted to or removed from trains. These are related to those where severe distress has been observed. Note that the track maintenance costs on the same base have risen somewhat, because the maintenance input has not yet stabilised. Maintenance has been held at bay by reducing energy transfer at sensitive sites. The current actual energy consumption correlates well with values predicted by computer simulation and it is therefore anticipated that the situation should stabilize shortly. The change from independently driven head-end plus in-train locomotive consists to head-end-only consists provided valuable insight into the adequacy or otherwise of the power supply. This was recognised as an important determinant of the magnitude and consequences of longitudinal locomotive/track forces. Inadequacy in this area later begets increased maintenance, for which the only palliative is ensuring adequate balancing speed by managing the spacing of trains.

The Sishen-Saldanha line: This line is older than the upgraded Ermelo-Richards Bay line, and has reached the equilibrium shown in Figure 6. This operation has occasionally experienced maintenance problems on older generations of car trucks and also on locomotive trucks. This has been accompanied by scattered lateral rail gauge face wear and has increased maintenance costs. Comparison of actual and simulated energy consumption has confirmed that the current slight rise in specific energy consumption should be investigated.

7 QUO VADIS?

This paper has reviewed the interrelationships between energy consumption, wheel/rail wear and track maintenance in high tractive/braking effort operations. Does this offer direction regarding future investment opportunities? By virtue of using straight electric locomotives, Spoornet already applies power ratings of 15.6MW (21 000HP) in traction and 18MW (24 000HP) in dynamic braking in heavy haul service. State-of-the-art power electronics and asynchronous traction motors offer significantly higher ratings. Although present substation capacity tends to limit tractive power, around 20MW (27 000HP) of dynamic braking per four-locomotive consist is commercial reality. A question which bears contemplation is whether higher installed power ratings will necessarily contribute solely to increased train performance, or whether a disproportionate amount will seep away to increased track maintenance? This raises the question of how much power per axle should be contemplated if "universal" locomotives were also to be deployed in heavy haul service. The author is of the opinion that train handling would have to be tightly managed to avoid drastically increased energy consumption.

8 CONCLUSION

It is concluded that train handling is a significant determinant of longitudinal track loading and hence of related track maintenance costs. The latter may be reduced by managing both energy input and superfluous energy consumption. Energy efficiency then becomes a useful yardstick with which to determine whether or not something is amiss. Computer simulation can be tuned to actual driving practices and is therefore useful to predict, compare and correct energy consumption.

9 REFERENCES

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