Some concepts for maximising renewable energy in railway traction

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Abstract - **This paper examines relationships among railways and renewable energy to discover in what ways there may be advantage in optimising their systemic interaction. It concludes that inherently competitive railways should be deconstructed into four sub-modes, high speed, heavy haul, heavy intermodal and urban rail, each of which optimises it energy consumption in a unique way. It presents a case study that illustrates how the relationship between railways and renewables might look in 2050.**

Keywords - **railway, renewable, genetic technologies, traction, competitiveness.**

I. Introduction

1.1. Rail's provenance and prospects

With Planet Earth seemingly headed for global warming straits, and transport energy consumption contributing substantially to that problem, rail as the preeminent energy efficient transport mode is set to reclaim and perhaps exceed its former prominence in land transport. It is expected to contribute an increasing base load of the global land transport task over the medium to long term, and even to capture an increasing share of the surface transport market from maritime transport. While rail is known to be an energy-frugal mode, the tenet of this paper is that if its positioning is not well aligned to its strengths, then it cannot play an optimum role.

From its early-1800s naissance rail grew vigorously to dominate land transport in the first half of the 20th Century. So much so that many governments nationalised or regulated their railways to curb the latter's perceived monopolistic hold on domestic economies, which dulled their competitive edge and damped their response to post World War II market- and technological opportunities. Consequently they declined as burgeoning air- and road transport eroded their established markets. Nevertheless, railway renaissance did emerge with Japan's 1964 entry into the high speed market space, followed by recognition of heavy haul in 1972, introduction of heavy intermodal or double-stacked containers following US railroad deregulation in 1980, and contemporary urban rail following economic globalization in1989.

Contemporary rail has subsequently experienced a second set of vigorous growth curves in each of the aforementioned market spaces. Private sector participation, and in heavy haul also direct private investment, has underpinned much of the investment needed to place the mode on these new growth curves. Consequently there has been a return to focusing on customer preferences, and renaissance rail is once more in touch with the commercial action. Appreciate that renaissance has not yet spread to railways in all countries, and what follows therefore is not applicable to countries that, for whatever reason, have not yet revitalised their railways.

1.2. Rail's relative energy efficiency

To affirm rail's energy efficiency, the author constructed Fig. 1 to show rail's robust position of in terms of ratio of transport unit share to energy consumption share, using energy consumption and modal share data published by the International Energy Agency in collaboration with the International Union of Railways [1]. Note that although the countries exhibit similar patterns, the values vary widely, particularly with respect to rail. The collaborative effort has thus far only produced data for the three years 2012-2014 and, although it is the most valuable data available in its field, it would seem to require more time to stabilise. Nevertheless, here it is presented at face value.

To limit climate change to a 2-degree target, the International Energy Agency recommends an *Avoid, Shift and Improve* approach with increased investments in rail infrastructure. *Avoid* refers to improving total transport system efficiency through integrated land-use planning and transport demand management, which is outside the scope of this paper. *Shift* is from energy intensive transport modes to more environmentally friendly modes, while *Improve* refers to vehicle energy efficiency, optimised transport infrastructure and use of alternative energy. The author therefore elected to address the *Shift* and *Improve* opportunities.

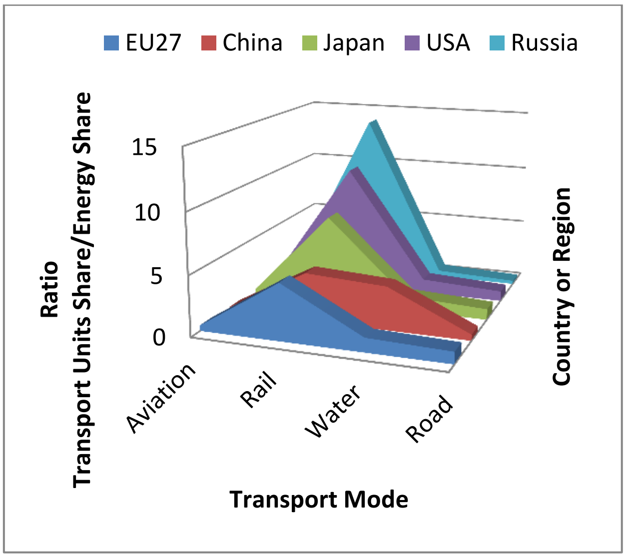

Fig.1, Relative energy efficiency of transport modes.

Railways uniquely combine high speed, high capacity and low rolling resistance to compete in market spaces where the pipeline, waterborne, road, and air transport modes cannot, more so as rising energy prices reflect its increasing cost of production. Although their energy consumption is inherently frugal compared to other modes, optimal alignment among railway- and renewable energy precepts requires recognition and consideration of perspectives developed in this paper.

1.3. Rail's energy consumption

Rail's energy efficiency essentially spins off from the three genetic technologies that distinguish it from all other transport modes. The first genetic technology, Supporting, which enables heavy loads, requires a strong interface between wheel and rail to sustain heavy axle loads. Rail's steel-wheel-on-steel-rail system deflects minimally to develop only a small contact patch between them, and rolling resistance is therefore very low. By contrast, road's rubber tyre contact patch is materially larger, requiring greater deflection particularly of the tyre, which increases rolling resistance and hence energy consumption. The second genetic technology, Guiding, which supports travelling at high speed, in turn allowing more potential energy to be converted to kinetic energy and vice versa over undulating gradients, thereby reducing both traction energy consumption and braking energy dissipation. High speed also reduces journey times, and hence reduces the period of time over which auxiliary equipment such as heating, ventilation, air conditioning and lighting must operate. Consequently high speed passenger trains actually consume less energy per passenger for a given journey than conventional passenger trains [2]. The third genetic technology, Coupling, which leverages Supporting and Guiding by joining many vehicles together to maximise capacity, averages grades under a train and therefore reduces both traction energy input and braking energy dissipation, particularly for long, heavy freight trains that travel at comparatively low speed. It also reduces aerodynamic drag because the frontal area of a train in relation to its length is small compared to any other transport mode—for example the ratio frontal area to vehicle length for a TGV Duplex train is one tenth that of an Airbus 380 aircraft, both double deckers.

A more comprehensive description of rail's genetic technologies and how they underpinned the railway renaissance may be found in [3].

1.4. Rail's energy consumption sweet spot

Rail therefore occupies an energy consumption sweet spot that other transport modes cannot match. All other things being equal, resistance to motion directly influences propulsion energy consumption. As shown in Fig. 2 [4], rail essentially undercuts the resistance to motion, expressed in Newtons per tonne, of all other transport modes. Relative to pipeline, rail offers lower resistance from speeds higher than ≈3km/h. Relative to maritime in displacement mode, where resistance rises exponentially with speed, rail offers lower resistance from speeds higher than ≈20 knots (≈40km/h). In addition to being slower, maritime routes can also be longer, for example Beijing to Athens Piraeus is 16000km by sea but only 8500km overland, which compounds rail's relative advantage. Relative to road trucks, rail always offer lower resistance, ≈50% at low speed, increasing to ≈80% at 100km/h. Relative to aviation, resistance is also always lower although rail cannot match its top speed. Nevertheless, rail can

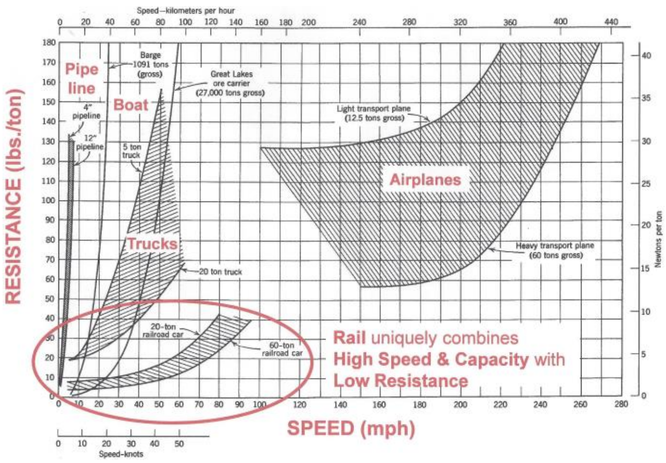

Fig. 2, Rail's energy efficiency relative to other modes

be competitive on centre-city to centre-city journey times, e.g. the fastest current Beijing to Wuhan schedule averages 285km/h over 1229km, a performance that aviation would be hard put to beat when accounting for time to commute to an airport, check in, check security, reclaim baggage, and commute to destination, in addition to scheduled flying time.

1.4. Methodology and scope

Having established a broad introductory framework within which to comprehend rail's energy consumption drivers, this paper henceforth examines in some detail key railway-energy positioning attributes and principles in the real world. It will start with examination of rail's four inherently competitive sub-modes against the general principles, followed by a brief case study of a significant association of renewable energy with rail. This will lead to the conclusions.

Although successive technology generations will introduce incremental energy efficiencies, they are unlikely to result in breakthrough rail contributions to the global transport task. This paper therefore focuses on positioning railways with respect to the effectiveness of their energy management.

Furthermore, this paper does not consider aspects that would apply to all transport modes, e.g. energy efficiency of escalators and lighting at stations and terminals, which do not differentiate one mode from another. Rail will only find its future in technologies that differentiate it from other modes.

II. Renaissance rail

2.1. Railway 101

Rail traction rests on relatively low steel-wheel-on-steel-rail adhesion: Relating it economically to locomotive trailing loads thus requires easy ruling grades. True, high speed trains accept much steeper ruling grades, but then performance expectations are so much higher that a high proportion of motored axles is typically required. Rolling resistance can be so low that heavily loaded freight trains require braking to maintain constant speed on descending grades as flat as ≈1‰. Thus long-haul railways operate in a domain where trains frequently generate instantaneously surplus energy quanta that are too large for on-board storage by known energy storage systems: Such energy must either be dissipated on board, or conducted away to alternative use or storage. This position relates to development of rail's inherent competitiveness.

Cross-breaking rail's genetic technologies Supporting and Guiding yields four inherently competitive railway sub-modes, namely high-speed, heavy haul, heavy intermodal (double stacked containers), and contemporary urban rail. Each is developing along vigorous new growth curves, which have offered individual energy positioning research opportunities, the findings of which follow. Appreciate that these sub-modes are sufficiently different that they cannot be optimised simultaneously within the same train-infrastructure system. Ideally they should each have their own infrastructure as is the solution emerging in countries such as China and India. Where there is insufficient traffic to justify separate infrastructure, they may of necessity be combined, but at best it will then be possible to optimise only one of them. This is well illustrated by the generally inferior performance of freight rail in Europe, and long distance passenger rail in North America.

2.2. Renewables 101

This section is not a comprehensive review, but its perspective is sufficiently wide to explore significant relations between railways and renewable energy.

Recall that rail's rolling resistance is very low, and its power and braking requirements are therefore largely determined by passage of trains over undulating gradients, although the power required overcoming aerodynamic resistance does rise as the cube of speed. The result is typically wide swings in propulsion and braking demand, and it is therefore desirable for trains to be able to interchange energy in both directions with their environment. Railways and renewable energy are thus natural allies, particularly when railways are connected to a large grid that can also store instantaneously surplus energy in real time. Trains should then be able to either consume or regenerate energy without restraint.

This makes long-haul trains natural adjuncts to smart grids, with all that that entails. Enabling smart grids requires a market and system manager to incorporate and manage centralised and distributed power generation, intermittent sources of renewable energy like wind and solar power, allow consumers to become producers and export their excess power, enable multi-directional power flow from many different sources, and integrate real-time pricing and load management data [5].

For scale, locomotives and wind-turbines are of similar size, mostly in the range 2-6MW. Thus intermittent railway energy consumption and regeneration rating and behaviour is similar to that of many renewable sources. While railway electrification infrastructure is an expensive energy supply and management on-cost, one advantage of guided transport over autonomous transport is that electrification need be confined only to the route defined by the track.

There appears to be little enthusiasm for hydrogen fuel cells in railways, other than possibly shunting or switching operations in yards. This outcome seems justified in situations where it is possible to conduct electric energy directly from wind or wave to train traction motors, with of course the requisite intermediary system.

2.3. The high-speed sub-mode

Chronologically, high speed was the first railway renaissance sub-mode. Japan's Tokaido Shinkansen, the world's first dedicated high speed line, was built to a ruling grade of 20‰, toward the steeper end of the conventional railway grade spectrum, but a subsequent uptick to as high as 40‰ has occurred. High-speed trains need a power rating of some 20kW/tonne to overcome aerodynamic drag and are therefore sufficiently powerful to operate on steep ruling grades. Nevertheless, despite aerodynamic drag being significant, it may not be sufficient to negate the need for braking on steep downgrades. Noting that the grade of repose is that on which rolling resistance (which increases with speed) equals gravitational resistance (which increases with grade), it is evident that the steeper the grade of repose, the higher the train's speed should be [2]. Thus the ultimate objective is not only high speed per se, but a sufficiently high top speed that allows wide enough operating speed variation within which to minimise traction energy consumption and braking energy dissipation over undulating terrain.

In addition to shorter journey time, curve resistance, and the energy consumed to overcome it, virtually fall away, because by nature high speed routes require large radius horizontal curves of some 7000m, to avoid curve speed restrictions. Note furthermore, they require vertical curves of some 55 000m radius to limit passenger discomfort as well as wheel loading and unloading. The steeper the ruling grade, the less nature is disturbed to achieve an acceptable alignment, and of course the lower the construction cost in carbon footprint and monetary terms. Vertical curves of 55 000m are a challenge in most terrains too. Appreciate therefore that even relatively easy terrain can pose a costly challenge for high speed railway builders. Thus unsurprisingly 87% of the Beijing Shanghai railway is elevated. Similarly, lines built after Japan's Tokaido Shinkansen all feature 85% of more bridges and tunnels. Where nature's challenges are too great, the only way out is to conceive an ideal alignment in space from journey time and energy consumption perspectives, and then close the gap by elevating or tunnelling as required. The essence of high speed is thus to **shift** and **improve**.

2.4. THE HEAVY HAUL SUB-MODE

Heavy haul became the second railway renaissance sub-mode when North American heavy freight train practices and standards were adopted rapidly throughout the world, usually on dedicated lines. As global coal and iron ore demand burgeoned, traditional sources became depleted or constrained by environmental impact, and mining gravitated to larger deposits in the world's remoter regions. From throughput baselines measured in tens of million tonnes per annum (Mtpa), many heavy haul railways currently convey hundreds of Mtpa. Their trains run loaded from mines generally at 30-40 tonnes/axle, returning empty from ports or power utilities at ≈5 tonnes/axle: Potential energy can theoretically supply all motive power needed, e.g. a mine at ≈800m elevation can support a 500km self-sufficient route, but balancing instantaneous deficits and surpluses attributable to gravity and false rise and fall in real time requires external energy storage of a quantum that only pumped storage can provide [6].

Practical heavy haul locomotive rostering dictates that the same number of locomotives should haul empty trains as haul loaded trains, so opportunistic alignment designers provided asymmetrical ascending ruling grades, flatter in the loaded direction and steeper in the empty direction, to make locomotives work hard in both directions. However, locomotives cannot electrically brake more than they can haul, so to maintain steady speed on long descending grades, it is necessary to brake the train wheels as well, so that total energy dissipation is split between friction on wagon wheels and locomotive braking resistors. With diesel traction, there is no way to provide sufficient on-board storage for electric energy dissipated by braking resistors, of the order of 10MWh, so the surplus is simply lost to the atmosphere as heat. Enter electric traction, and the scenario changes dramatically. Because overhead catenary is present, it is theoretically possible to regenerate energy for use by other trains or to return to the grid. However, the portion dissipated by friction braking on wagon wheels, of the order of 50%, is unavoidably lost. If speed is reduced so that no contribution from friction brakes is needed, the locomotives alone cannot sustain sufficient adhesion to brake on the steeper downgrade what they can haul on the flatter upgrade. The only solution therefore is to return to symmetrical grades, which would be prohibitively expensive except on new lines [7]. As with high speed, optimising heavy haul energy consumption applies the same principles but results in a different systemic solution. The essence of Heavy Haul is to **improve** energy efficiency.

2.5. THE HEAVY INTERMODAL SUB-MODE

The third railway renaissance sub-mode, heavy intermodal, emerged after United States railroad deregulation released pent-up innovations. Noting that adding value to raw materials and intermediate goods reduces their density, it is not possible to maximise the Supporting genetic technology contribution when railing high-value semi-finished and packaged finished goods. Double stacking ISO containers on railway wagons to achieve high axle loads provided the competitiveness breakthrough that rail needed. It has subsequently spread to the entire North American Free Trade Agreement, Australia, China, India, and Panama, as well as Saudi Arabia and the other Gulf Cooperation Council States. Such trains attain 120km/h, but require braking on grades steeper than ≈5‰ despite the higher aerodynamic drag of double-stacked containers [5]. While overhead electrification is frequently held to be an impediment to double stacking, this is only true for existing infrastructure. New infrastructure can be built with the required vertical clearance, and pre-existing infrastructure can be cleared for double stacking, as has been done at many sites in North America. Although most double stack trains are hauled by diesel locomotives, catenary cleared for double stacks does exist, for example on portions of the US Northeast Corridor, on India's under-construction Western Dedicated Freight Corridor, and some routes in China, so exporting energy from such trains for re-use or storage is practicable.

Even when using diesel traction, double stacking **shifts** road traffic to rail for a 3½ to 1 fuel saving. Now containers on rail are challenging maritime transport in the same way. As a rule of thumb, rail transport is around half the cost of air freight and twice as fast as sea transport [8], which makes it particularly relevant to low density high value freight in the very long haul market space. Thus over the last five years several regular 9000km to 13000km container hauls from China into Western Europe and vice versa have been established [7]. These routes do not operate double stack trains yet, and portions of them are electrified, but once they have bedded down and traffic approaches line capacity, expect upgrading of infrastructure to accommodate double stack container trains.

2.6. THE URBAN RAIL SUB-MODE

The fourth and last railway renaissance sub-mode, urban rail, is characterised by frequent trains at 1½-5 minute headways during peak times in essentially closed systems where trains return cyclically to the same elevation with neither net potential energy gain nor loss. Urban rail is always a net energy consumer: Sourcing renewable energy depends on host city arrangements, or availability of supplier choice.

Urban rail traction technology has arrived at the interesting position where the components of energy consumption and their provision over the stop-to-stop duty cycle may be separated and each managed to best advantage. Because speed is relatively low, aerodynamic resistance is not a major factor, and the remaining items in the duty cycle are accelerating from a stop, maintaining speed, and retarding to the next stop. Of course, auxiliary services such as heating, ventilation, air conditioning, lighting and infotainment also consume energy. Energy regenerated during braking can be stored and reused for acceleration, so the net external energy required is that to make good irreversible losses, drive auxiliaries and account for elevation differences between consecutive stations.

Traditionally, external energy requirements were provided continuously via ground or overhead systems, or a mixture of both as for example Bordeaux's trams. The recent emergence of lithium ion batteries and ultracapacitors of sufficient capacity has however changed the game. It is now possible to recycle a significant portion of the energy required over the duty cycle on board, and to revisit the external supply arrangements. The smaller external portion does not necessarily require continuous conductors and can therefore be provided intermittently by inductive power transfer at standstill during station dwell time. This is an attractive option in situations where visual intrusion of overhead traction equipment is not acceptable. It does however complicate feeding arrangements, and at present is used at the lighter end of the rail spectrum, namely trams and light rail vehicles. Note also that intermittent inductive power transfer is not confined to the rail mode, but could equally be applied to bus rapid transit and other road vehicles. This could be an equalising technology between rail and road, although road will always attract a significant energy demand disadvantage due to its higher rolling resistance.

Where significant elevation differences exist and potential energy needs to be factored in, as well as in heavy metro systems with high power requirements, continuous external supply is still required. The latter systems typically have high diversity and small lineside storage devices usually suffice to stabilise supply voltage. Systems have recently also become available to return small amounts of surplus energy to the grid to achieve the same end. Smart systems therefore merely level peaks. First priority is to re-use energy within the sub-system where it originated; second priority is to export it to a higher level system or the grid. Early kinetic energy storage systems were in fact installed on board. Nevertheless, storing instantaneously surplus energy on board is also questionable, because demand variance is highest at the level of individual electric multiple units. Exporting surplus energy of course incurs losses, and the jury is still out on the optimum solution.

In contrast to the first three sub-modes of the railway renaissance, the scope for structural reduction in urban rail energy consumption is therefore small. Its natural development trajectory is to **Improve**. Thus the European Union funded Osiris project addresses energy efficiency in the entire urban rail system, including vehicles, infrastructure and operation [9]. However, in the big picture the value of urban rail is to **shift** passengers from road to rail in transit oriented urban development.

III. POST-RENAISSANCE RAIL IN 2050

3.1. THE VISION

The year 2050 is widely regarded as a datum by which transport should have achieved sufficient emissions reduction. For example, the European Commission's White Paper on Transport [10] implicitly incorporates precepts developed in this paper in several visionary passages such as: Break transport's oil dependence without sacrificing efficiency and compromising mobility by using less and cleaner energy, exploiting modern infrastructure and reducing environmental impact [Page 6]. Resource-efficient vehicles and cleaner fuels will not cut emissions sufficiently, so consolidate large volumes over long distances into buses, coaches, rail and aviation for passengers, and multimodal waterborne- and rail-based solutions for long haul freight [Page 7]. Ensure structural change to enable rail to compete effectively and take a significantly greater share of medium- and long-distance freight and passengers [Page 7]. By 2050, complete a high-speed rail network and maintain a dense conventional railway network for the majority of medium-distance passengers to use rail; connect all core network airports to the rail network, preferably high-speed; ensure that all core seaports are sufficiently connected to the rail freight system [Page 9]. The following section shows how it might be done.

3.2. A CASE STUDY: LANZHOU–XINJIANG CONVENTIONAL AND HIGH-SPEED RAILWAYS

As a preview of how the four inherently competitive railway sub-modes might serve countries and continents in 2050 using renewable energy, it is instructive to examine the above route.

For the avoidance of doubt, there are two separate railways between the city of Lanzhou and Xinjiang Province in China. The so-called Lanxin conventional freight- and passenger railway opened in 1966, and the so-called Second Railway, a 1776km 250km/h high speed line serving regional capital city Ürümqi, opened in 2014. Metro railways are under construction in Lanzhou for completion in 2016, and in Ürümqi for completion in 2018. The corridor aligns with China's *Go West* development strategy and revival of the ancient Silk Road trade route into Central Asia and beyond. The Lanxin railway conveys both coal and containers, and continues beyond Ürümqi, bifurcating into northern and southern border crossings with Kazakhstan. The former eventually links with the Trans-Siberian railway to access northern Europe, while the latter is being developed to access Southern Europe via a Caspian Sea ferry and Turkish Railways. China's Gansu wind farm, with current nameplate capacity of 12.7GW and planned increase to 20GW by 2020, is located in a region of abundant wind resources [11] through which both railway lines pass.

On global scale this megaproject stands out as example of integration between continental, regional and urban spatial development; high speed-, domestic, international and intercontinental freight-, and urban railways; and renewable energy. High-speed rail has been deployed on a very long haul by comparison with systems outside China, where journey time was held to 3-5 hours or less, substituting trains for aviation. Although acceptability depends on people's time value, rail can move large numbers of people over long distances consuming less energy than aviation. This case could well be a prototype of railways around the world in 2050.

IV. Conclusions

On an installed-power comparative scale, long-haul locomotives, multiple-unit trains, and wind turbines share comparable power ratings and intermittent behaviour. Thus, railways and renewable energy were found to have natural synergy. Exploiting that synergy is however contingent on deploying electric motive power connected to a grid that supports independent power production, -bulk real time storage and -system operation.

The pieces on each railway renaissance sub-mode have been superficial, and deeper examination reveals interesting facets of relations between the nature of railways and the energy that they consume. An important conclusion regarding renewable energy is that while each of them is a good fit with renewables, they each optimise their contribution in a different systemic way. There is no one-size-fits-all solution. There are many non-energy-related reasons why systemic optimisation would have the four sub-modes to be physically separated, and factoring in energy considerations simply adds more reasons. This is a useful finding, because where available traffic density may appear insufficient to justify separation, the energy dimension calls for diligent reconsideration.

From a philosophical perspective, it is worth noting that the pursuit of low energy consumption in railways has positive spinoffs in maintenance areas as well. Aerodynamic losses do not result in wear, and electrical losses turn into heat, neither of which, within limits, damages equipment. However, any energy dissipated by mechanical friction constitutes an irreversible loss that degrades something, and railway systems contain many elements intentionally or unintentionally designed to dissipate energy, such as dampers and drawgear. Ballasted track in particular closely resembles the gravel arrester beds designed to catch runaway road vehicles on steep downgrades, so its energy absorbing properties are well known. Trains that use more than the absolute minimum of traction and braking simply dissipate it in wear and tear including of the huge energy sink on which many of them run.

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