Grid-connected vehicles as the core of future land-based transport systems

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Abstract

Grid-connected vehicles (GCVs)—e.g., electric trains, metros, trams, and trolley buses—are propelled by electric motors directly connected to remote power sources. Their low at-vehicle energy consumption and ability to use a wide range of renewable energy sources make them strong contenders for urban and inter-urban transport systems in an era of energy constraints that favours use of renewable fuels, which may lie ahead. Needs for autonomous motorised mobility could be acceptably met in large measure by deployment of personal GCVs, also known as Personal Rapid Transit (PRT). Alternatives, including fuel-cell vehicles and dual-drive vehicles fuelled with ethanol, will be less feasible. The 'car of the future' may not be an automobile so much as a PRT element of a comprehensive GCV-based system that offers at least as much utility and convenience as today's transport systems.
Running head: Grid-connected transport systems

Keywords

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1. Introduction

The century-long predominance of the internal combustion engine (ICE) as the propulsion unit for land vehicles is beginning to end. The ICE is being displaced, at least partially, by the electric motor (EM), which has been in use all along—in trams (streetcars), trains, and some other vehicles—but is now appearing in personal vehicles, including cars (automobiles), passenger vans, and sport-utility vehicles. Key questions concern the nature and speed of the transition, whether the EM will completely replace the ICE, and how EMs will get their electricity, from ICEs, batteries, fuel cells or in other ways.

In a useful contribution to these considerations, Romm (2005)—and also Romm and Frank (2006)—proposed that the car of the future will be a dual-drive vehicle with an EM and an ICE. The EM will be powered by a battery that can be charged by the ICE or, when the car is stationary, from the electric grid. The battery will have sufficient capacity for the car to be driven on the EM alone for up to 40 miles (about 64 km). Ideally, Romm proposed, the grid electricity used for the (off-peak) charge will be produced from renewable resources. The ICE's fuel will be a mixture of 17% gasoline and 83% cellulosic ethanol by volume. Such a vehicle, Romm suggested, could travel 500 miles on a U.S. gallon of gasoline (equivalent to about 0.5 L/100 km), resulting in only one tenth of the greenhouse gas (GHG) emissions produced by current dual-drive cars (also known as hybrids).

We endorse much of Romm's vision, particularly the potential value of dual-drive cars that can be charged from the grid, called e-hybrids by Romm and also known as plug-in hybrids. Compared with today's cars—including presently marketed hybrids (which cannot be so charged)—such vehicles promise substantial reductions in petroleum use and at-vehicle emissions, and reductions in overall emissions according to how the electricity is produced (McCleese and LaPuma, 2002).

E-hybrids promise an appealing path away from current dependence on petroleum products to fuel our mobility, albeit at a cost. The path is appealing because e-hybrids can have all the attributes of today's cars, particularly their power and range, while using less energy overall and much less petroleum during local travel. However, even with substantial economies of scale, e-hybrids will be intrinsically more costly than regular cars because two drives must always cost more than one, and more costly than current hybrids because large batteries must always cost more than small batteries.

We differ with Romm in several respects, which this paper elaborates:

1. We share Romm's concern to reduce anthropogenic GHG emissions but believe there is a more urgent issue: transitioning to an imminent era of severe energy constraints as peaks are reached in world production of liquid and then gaseous petroleum products.

2. Even with e-hybrids' sparing use of ICE fuel, there is unlikely to be sufficient affordable ethanol or gasoline to support other than modest levels of non-electric propulsion.

3. In an energy-constrained world, particularly one favouring renewable resources, transport and other energy-intensive systems will optimize to the lowest energy use consistent with a range of energy sources. In practice, this will mean widespread deployment of vehicles with EMs connected to the grid *while in motion*. Such grid-connected vehicles (GCVs) are familiar in public transport service, notably as inter-city trains, metros (subways), trams (streetcars), and trolley buses. We argue that energy constraints will impel deployment of other types of GCV, including personal GCVs (also known as Personal Rapid Transit, or PRT), trolley lorries (trucks), and others. We will suggest that e-hybrids could provide a path to GCV-based land transport systems. E-hybrids will not be the car of the future but a step towards the personal transport system of the future.

2. Energy constraints

We believe that the urgency of the energy predicament of industrialized and other countries is well established (Bentley, 2002; Hirsch, 2005a, Campbell, 2006, Dorian et al., 2006). Indeed, without wanting to discount the concern about potential climate change, we will suggest that imminent energy constraints could present more immediate challenges to the survival of our global civilization.

According to the International Energy Agency, oil consumption (demand) is projected to increase by 41% between 2004 and 2030 (IEA, 2005a), from 82.1 to 115.4 million barrels/day (mb/d). Fig.1 shows how most of the supply required to meet such increased demand—and replace currently depleting resources—is expected to come from OPEC countries in the Middle East, where production would have to increase by 93% between 2004 and 2030. Of this increase, by far the largest part (77%) is to come from Iraq, Iran, and Saudi Arabia (IEA, 2005a).

The availability of oil from Iraq is evidently unreliable at the time of writing; production fell in 2005 and may be falling again in 2006 (IEA, 2006). Iran's production may have peaked in 2004 (BP, 2006; IEA, 2006). Saudi Arabia's fields could be reaching their production limit (Simmons, 2005). According to an industry source, heightened drilling in Saudi Arabia may now be offsetting only a portion of the production decline from established wells (Platts, 2006). Thus, the prospect that IEA's (2005a) projection of oil consumption will be met seems low.[1]

Geologists and others have noted that of the 65 countries that have produced 'conventional' oil, 55 appear to be past their production peak (ASPO, 2006). They have concluded that world production of all petroleum liquids is peaking (Deffeyes 2005) or will peak during the next decade (Laherrère, 2004). We find particularly plausible the conclusion of (Aleklett and Campbell, 2004) that production will peak in or near 2012. Hirsch (2005b) concluded, "The data show that the onset of peaking can occur quite suddenly, peaks can be very sharp, and post-peak production declines can be comparatively steep (3-13%)". However, we note too that Jaccard (2005) has anticipated that world oil production will be similar in 2050 to production in 2000.

Other analyses have pointed to the extent to which oil prices could rise as a result of shortfalls between the demand trajectory—i.e., potential consumption—and the availability of oil. Perry (2001) suggested that a 10-per-cent supply shortfall could result in a more than six-fold increase in the price of crude oil, even allowing for some attenuation as a result of reduced demand. NCEP (2005) estimated that a four-per-cent shortfall would result in a 177-per-cent increase in the crude oil price (i.e., a factor increase of 2.7 times). Using the Long-Term Oil Price and

[1] IEA (2005) had already revised downwards its estimates of future world consumption and the contributions of OPEC Middle East countries. In its previous outlook, IEA (2004) had projected world consumption in 2030 to be 121.3 mb/d, vs. 115.4 mb/d in IEA (2005). More dramatically, whereas IEA (2004, 110) suggested, "Of the projected 31 mb/d rise in world oil demand between 2010 and 2030, 29 mb/d will come from OPEC Middle East", the equivalent increase in projected world demand for this period in IEA (2005) was 22.9 mb/d, of which 14.4 mb/d would come from OPEC Middle East.

Extraction (LOPEX) model, Rehrl and Friedrich (2006) generated a less leveraged relationship, but nevertheless pointed to a more than 11-fold price increase as a result of a shortfall of some 70 per cent.

Fig. 2 illustrates the 30% shortfall in 2020 between the demand trajectory in IEA (2005), shown in Fig. 1, and the supply trajectory in Aleklett and Campbell (2004). It may be reasonable to conclude that in 2020 crude oil prices could be several times higher than at present, and that retail fuel prices will also be much higher.

The prospect of such dramatic increases in oil and fuel prices could be regarded with optimism. They would speak to a measure of political stability and economic continuity that maintains markets for oil, albeit in economies that are much less dependent on petroleum products.

Transitioning towards the 'soft landing' of economic continuity and political stability in a world that has passed peak oil production will require timely preparation and major structural changes, particularly in the movement of people and goods. The extent of required change during the next few decades may be far more than is required to avert what Romm (2005) anticipated as "serious if not catastrophic climate change". A preoccupation with averting, rather than adapting to, climate change could be a distraction from the need to prepare for very high oil prices, especially if the anthropogenic contribution to ongoing climate change proves to be lower than anticipated (Khandekar et al., 2005; Moberg et al., 2005; Osborn and Briffa, 2006; Tunved et al., 2006). Moreover, anticipation of relatively imminent, very high prices may be a stronger stimulus to secular action than prevention of warmer winters, sea-level rise, and ecological changes, which are diffuse in impact and unpredictable in timing.

3. Uncertain prospects for biofuels

Romm's (2005) scenario of greatly reduced fossil fuel use depends strongly on maintaining widespread use of vehicles that carry their own fuels, specifically the e-hybrids noted above. Three such fuels are anticipated for each vehicle: electricity stored in batteries to drive the vehicle's EM, and a mixture of 83% ethanol and 17% gasoline for the vehicle's ICE. The result, he suggested, would be gasoline use in the order of 0.5 L/100 km and ethanol use in the order of 2.4 L/100 km.

Here we consider only U.S. use of light-duty vehicles (including passenger cars, vans, sport-utility vehicles, and others fuelled by gasoline). This movement totalled 4.4 trillion ($4.4\ 10^{12}$) vehicle-kilometres in 2004, having risen by 2.3%/y between 1994 and 2004 (BTS 2006). Persistence of this trend, which Romm seems to accept, would have U.S. light-duty vehicles moving 6.3 trillion kilometres in 2020. According to Heavenrich (2005) the urban share of this travel—as opposed to the 'highway' share—peaked in 1994 at 63%. Continuation of the subsequent decline would result in an urban share of 59% of these kilometres in 2020.

The urban share is the most relevant to use of the EM, and it may be reasonable to assume that Romm's anticipated gasoline and ethanol consumption rates apply only to this share. If the highway share in 2020 involves use of 1.0 L/100 km gasoline and 5.0 L/100 km ethanol—equivalent in energy terms to 4.3 L/100 km of gasoline, or about half the rated fuel use of 2005-model-year light-duty vehicles in the U.S. (USDOT, 2005)—the total U.S. consumption of ethanol for transport would be some 220 billion L. This amount is about *seventeen times* the total U.S. production of fuel ethanol in 2004, which totalled about 13 billion L (Urbanchuk, 2005). It comprised 83% of non-food ethanol production totalling 15.5 billion L (Tokgoz and Elobeid, 2006). (Gasoline use would fall by more than 90%, from 510 billion L in 2004 to 44 billion L in 2020.)

In the U.S., almost all non-food ethanol is produced from maize (corn), using 11% of the crop or about 32 million tonnes in 2004 and requiring about 3.2 million hectares of land (Urbanchuk, 2006). This was 2.3% of the land used for crops in the U.S. (Lubowski et al., 2006). Thus the 17-fold increase noted in the previous paragraph would, at present rates of production, require about 40% of U.S. cropland (i.e., about the same area that is now used to grow food).

Adding annual ethanol production of more than 200 billion L would require construction of more than 1,000 plants similar to the recently commissioned Goldfield plant in Iowa (Clayton, 2006; Konrad, 2006), which uses 100,000 tonnes of coal to produce 190 million L of ethanol annually from about 500,000 tonnes of maize. The ethanol's energy value is about 4.0 PJ. The energy input from the coal is about 2.9 PJ. A full account—including, for example, inputs for farming the crop and moving the coal and the maize to the plant—would bring the process closer to although not necessarily into a negative energy balance (Farrell et al. 2006).

To overcome the energy and land challenges inherent in current ethanol production, Romm proposed use of "cellulosic ethanol", produced by enzymatic processing of the presently unused lignocellulosic components of plant material. If this process were to become commercially available, it could require less energy and less agricultural land. According to Patzek (2005), such ethanol production would result in severe depletion of soil nutrients and unsupportable requirements for fertiliser. There would also be the high energy and financial cost of preprocessing the plant material, and the challenge of maintaining sterility in fermenter vessels across the relatively long dwell times required for enzymatic action. One analysis suggests production of cellulosic ethanol from wood waste may require *more* energy on a full life-cycle basis than conventional production from corn (Patzek and Pimentel, 2005).

Given these energy and land challenges, if e-hybrids are "likely to become the dominant vehicle platform by the year 2020" (Romm, 2005), continued reliance on petroleum fuels seems likely. Nevertheless, gasoline consumption would be lower even if no more ethanol were used than is used today. If in 2020 all passenger cars are e-hybrids, operating at the above energy intensities, but almost entirely on gasoline, gasoline consumption will be down by about two thirds. This would be a considerable achievement, but it may not be sufficient reduction in view of the potential for lower production and large price increases noted above. Moreover, large amounts of petroleum fuel could still be required for heavy-duty vehicles, which mostly perform highway travel and for which e-hybrid technology is less suitable.

4. Grid-connected vehicles (GCVs) offer a better solution

We believe even more strongly than Romm (2005) that future vehicles will rely on EMs. E-hybrids could be a path to the transport future we envision but they would not be the central feature of that future.

Electric vehicles offer lower at-vehicle energy use than vehicles reliant on ICEs. Table 1 compares vehicles that differ chiefly in their drive systems. One has an ICE using diesel fuel. Two have electric motors; electricity is provided by a battery in one of these and by a fuel cell in the other. Compared with the battery vehicle, the fuel cell and ICE vehicles use two and three times as much energy, respectively.

The fuel cell vehicle uses more energy than the battery vehicle because of losses in converting the carried fuel (hydrogen in this case) to electricity. The ICE vehicle uses even more because of the even greater conversion losses from the diesel fuel to kinetic energy.

In a ‘well to wheels’ analysis, other energy costs must be considered. For the ICE vehicle, they include those in extracting, producing, and transporting the diesel fuel, which can be low for conventional sources of oil, although much higher when oil is produced from oil sands or shale. For the fuel cell vehicle, they include the energy costs of producing hydrogen from natural gas (the source of most hydrogen today) or electrolysis (which could be based on renewable resources), and those in distribution and storage. For the battery vehicle, they include mostly the energy costs of generating the electricity, which could be high if it comes from a conventional coal-fired plant, and low if it comes from solar panels or wind turbines. There are minimal losses in distributing and storing electricity.

Romm (2005) suggested that “e-hybrids will likely travel three or four times as far on a kilowatt-hour of renewable electricity as fuel cell vehicles”. This will be true when hydrogen is produced by electrolysis because of multiplicative 50% losses in each of converting electricity into hydrogen and providing it to the fuel cell, on the one hand, and in the fuel cell itself, on the other hand (Bossel, 2004; USNRC, 2004).

For battery vehicles, the prime challenge is the low energy density of available batteries, which limits the range between charges. The e-hybrid solution to the range problem is provision of an ICE that can recharge the battery and replace the EM, using a fuel with much higher energy density.

Another solution to the limited range of battery vehicles is to feed electricity to the vehicle while it is motion. Such grid-connected vehicles (GCVs) are familiar components of many public transport operations. Most of the public transport trips made in Canada’s three largest cities are in GCVs. Such vehicles’ much lower energy use at the vehicle is illustrated in Table 2, which compares energy use by diesel buses, trolley buses, and light rail systems in the U.S. Again, the vehicles with EMs use only about a third as much energy at the vehicle as the vehicles with ICEs.

In the U.S., most electricity generation is at coal-fired generating stations (IEA 2005b), but renewable sources can be used for GCVs. In Calgary, the light-rail system is fuelled entirely by electricity from a dozen 660-KW wind turbines, transmitted across the Alberta grid. The system’s slogan is ‘Ride the Wind’, displayed on the side of the two-car train shown in Fig. 3.

Other applications for GCVs have included trolley lorries (trucks) used in off-road applications, particularly mines. Heavy-duty vehicles with EMs, drawing current via trolleys from overhead wires, have superior ability on steep gradients. EMs generate much more torque at low speeds compared with comparably sized ICEs.

Another familiar application of GCVs is the inter-city electric train, including the high-speed trains in Europe, Japan, and the U.S. The superior properties of EMs for train locomotives has long been recognized, particularly their near-constant torque at all speeds. Even on tracks where grid connection is not possible, rail traction units usually have EMs, with electricity provided by on-board diesel generators. However, for a given power output, such diesel-electric locomotives are more than twice the weight of an all-electric locomotive powered from an overhead wire (Anderson and Peters, 1991), and the energy use at the vehicle is several times higher.

In short, in terms of energy use and motive performance, GCVs provide numerous advantages that could well become more valued in an energy-constrained world, especially when much primary energy production comprises generation of electricity from renewable resources. The major disadvantage of GCVs is the requirement for infrastructure that can provide electricity to vehicles moving along the route, and the corresponding inflexibility of a system that, except for limited battery-powered operation, allows motorised travel only along such routes.

5. Personal GCVs

The inflexibility of GCV systems is especially apparent in comparison with today’s cars and lorries (trucks), which can move wherever there are roads and occasional refuelling stations. An alternative to the car, offering more flexibility than conventional public transport, could be a widespread system of personal GCVs, usually known as a Personal Rapid Transport (PRT) system. Such systems comprise fully automated, 1- to 6-person vehicles on reserved guideways providing direct origin-to-destination service on demand.

PRT has been mooted for decades (Anderson, 2005; Cottrell, 2005), and now seems poised for implementation (Buchanan et al., 2005). Systems are to be installed at Heathrow Airport between parking areas and terminals (ATS, 2006) and in the Dubai International Financial Centre (DIFC, 2006).

A recent assessment of PRT, conducted for the European Commission's Fifth Framework Programme, Energy, Environment, and Sustainable Development (NETMOBIL, 2005, 35), concluded,

> The ideal target of cities is a self financed public transport system. PRT has a relatively low capital and operating cost e.g. lower operating cost per passenger-km and lower capital cost per track-km than light railway. PRT can cover its operating costs, and has the potential to even cover capital costs depending on the type of network, the discount rate and a reasonable fare (corresponding to the increased efficiency and quality). In the longer-term, large-scale implementation and mass production of PRT will lead to reductions in cost.
>
> The total investment costs for guideway, vehicles and stations of a PRT system have been compared with different public transport systems. The investment cost in million Euros per track-km of three PRT systems has an average of 6 million euro per track-km. This value is lower than for all other systems considered (Automated Guided Transit, light rail transit, bus ways, and trolley bus routes).

6. Implementation of GCV-based systems

Available space does not permit extended treatment of implementation of a GCV-based land-transport system. For the moment, we sketch two pathways towards such a system.

One is the e-hybrid vehicle as proposed by Romm (2005), although with its ICE fuelled by gasoline or diesel rather than mostly by ethanol. Rather than see e-hybrids as an end point in the evolution of the light-duty vehicle, we see them as a transition vehicle towards grid-connection or full battery operation. Extensive use of e-hybrids could lead users to want more use of their EMs. To facilitate this, governments or entrepreneurs could provide powering means along major routes, accessible by appropriately equipped vehicles *while in motion*.

When such en-route powering is sufficiently extensive, EVs with only batteries and retractable tethers could prevail over e-hybrids. As the grid-connection system expands, the need for off-grid movement would decline. Roads could be supplemented and even replaced replaced by lower-cost guideway infrastructure. At the same time, vehicles would evolve to move only on the guideways. They would be as light as possible and, where appropriate, be assembled into trains. They would comprise PRT.

Another pathway could involve the evolution of public transport towards supplementation of or even replacement by PRT. This would be driven by PRT's low energy cost and, perhaps even more, by its potentially low infrastructure cost, discussed in the previous section. If fuel prices for cars increase steeply, civic administrations will be pressed to provide alternative means of local travel. PRT could prove to be an attractive option, whether or not the above-noted evolution of the car has occurred. An analysis for Corby, a community of about 55,000 residents about 150 km north of London, UK, compared costs of PRT and light rail. For similar initial investment, operating costs, and fare structure, the PRT system would carry almost twice as many passengers annually, resulting in coverage from revenues of both operating and capital costs. Revenues from the light rail system would cover operating costs only, resulting in a net loss per rider of about 25% of the fare paid (Bly and Teychenne, 2005).

7. Conclusion

A recent analysis of the evolution of "how critical consideration of automobility has evolved over the last three decades" (Cohen, 2006, 24) built on a 2001 statement by the chief executive of the Ford Motor Company, William Clay Ford Jnr: "The day will come when the notion of car ownership becomes antiquated. If you live in a city, you don't need to own a car." Cohen (2006, 34) noted that " A century ago … it was inconceivable that mass motorization would become a ubiquitous form of personal conveyance in virtually all developed countries (and an expanding number of developing nations)" and also that "it is highly unlikely that anything even remotely related to the current motorcar will endure into the next century". We believe that if there is to be motorised movement of people in cities 100 years from now, most of it will be in GCVs where PRT systems extend the scope and type of mobility offered by EMs.

Recently Peter Hall, among the UK's best known urban planners, said, "…if [the Heathrow PRT system] is as successful as I think it will be, this could be a big breakthrough in developing new kinds of totally personalised rapid transit, which could transform our cities in ways that we can't yet see." (Hall, 2005).

PRT may well transform our cities, but its more important function could be to maintain the option of personal motorised transport in an era of severe energy constraints. From the perspective of 2006, only a mix of familiar GCVs—e.g., metros and trolley buses—and PRT could offer the comfort, convenience, and comprehensiveness of today's transport when available fuels are mostly renewable.

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Fig. 1. IEA's indication of sources of supply to meet projected world demand for oil until 2030

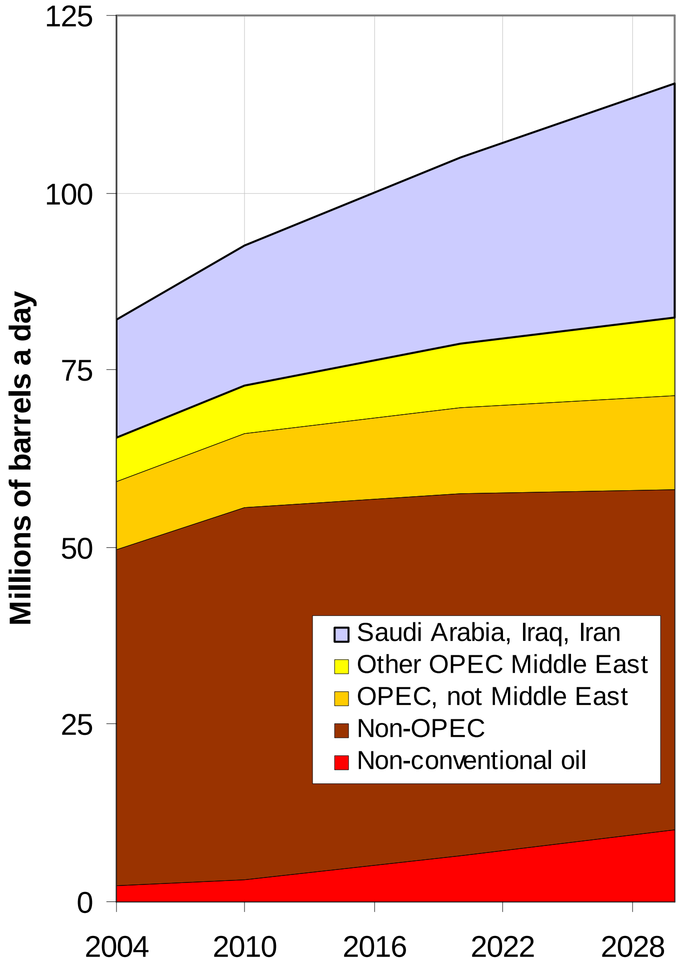

Fig. 2. Potential shortfall in production of petroleum liquids in relation to projected consumption

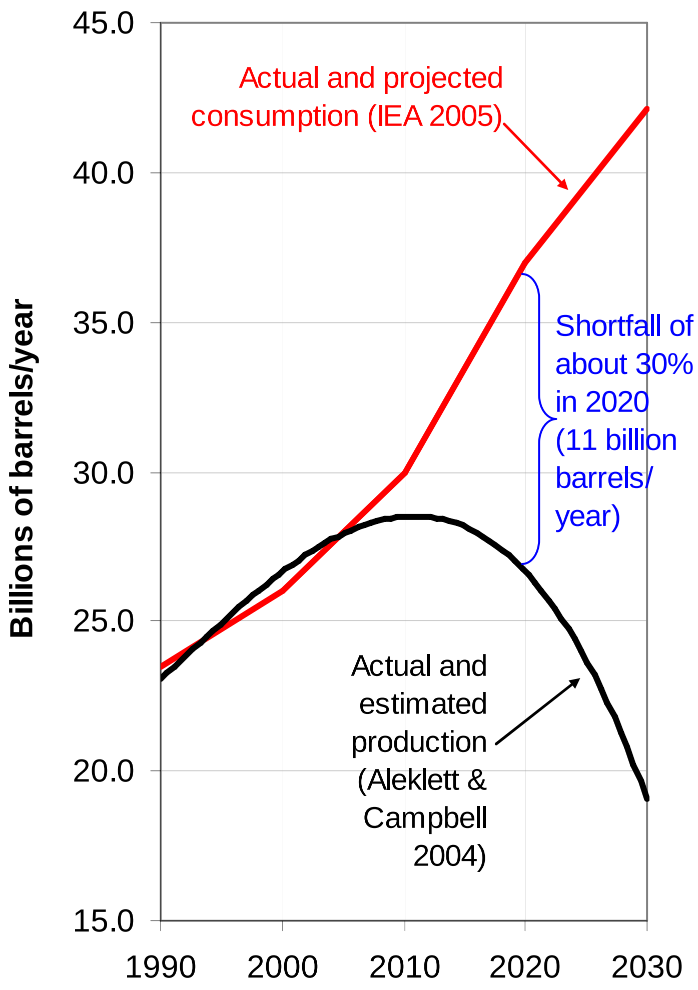

Fig. 3. Wind-powered light-rail train in Calgary, Alberta,

Table 1. Features of modern ICE, battery, and fuel cell automobiles

	ICE[1]	**Battery**[2]	**Fuel cell**[3]
Length (m)	4.25	4.49	4.17
Width (m)	1.76	1.77	1.76
Height (m)	1.46	1.45	1.65
Unladen weight (kg)	1,200	1,590	1,670
Seats	5	5	4
Drive (2 or 4 wheels)	2	4	2
Max torque (Nm)	119	518	272
Max power output (kW)	61	50	86
Max speed (km/h)	171	180	150
Range (km)	820	250	430
Rate of use of energy at the vehicle (MJ/100km)	209[4]	69[5]	124[6]

[1] 2005 Honda Civic 1.4 (Honda 2005a).

[2] 2005 Mitsubishi Lancer Evolution MIEV (Mitsubishi 2006).

[3] 2005 Honda ZC2 (Honda 2005b).

[4] Based on the stated 6.1 L/100 km, at 34.2 MJ/L.

[5] As estimated by Bossel (2005) from information provided in the source about the batteries (95 Ah rating; 14.8 volts; 24 modules) and the indicated range.

[6] Based on the stated storage capacity of 3.75 kg hydrogen (at 142 MJ/kg) and the indicated range.

Table 2. Comparison of public transport modes (U.S. data for 2004)[1]

Mode[2]	Average speed (km/h)[3]	Average occupancy (passengers/ vehicle)	Energy use at the vehicle[4]		
			Average, MJ per vehicle-kilometre	Range, MJ per vehicle-kilometre	Average, MJ per passenger-kilometre
Diesel bus	13.2	10.2	23.1	5.4-39.6	2.40
Trolley bus	7.9	13.3	11.3	9.1-20.0	0.85
Light rail[5]	15.9	23.2	18.1	9.1-34.1	0.78

[1] The data in this table are based on USFTA (2006).

[2] All U.S. trolley bus fleets (four in total) and light rail fleets (26) are represented in the table, but only 154 out of the 525 diesel bus fleets providing local public transport service in the U.S. Excluded were bus fleets operated by the private sector, fleets for which other fuels were used as well as diesel fuel, and fleets for which there were evident data anomalies.

[3] Speed and occupancy data refer to in-service vehicle-kilometres (vkm) only.

[4] Energy use data are based on *all* vkm, on average 13.9% higher than in-service vkm for diesel buses, 3.1% higher for trolley buses, and 1.9% higher for light rail. Energy use per passenger-kilometre is average use per vkm divided by occupancy.

[5] For light rail, ‘vehicle’ means one carriage (car). Thus, a two-carriage light-rail train counts here as two vehicles. For diesel and trolley buses, each bus counts as one vehicle whether or not it is articulated.