TETHERED VEHICLE SYSTEMS FOR SUSTAINABLE TRANSPORT IN DEVELOPING COUNTRIES

Richard Gilbert
Centre for Sustainable Transportation
15 Borden Street, Toronto, Ontario M5S 2M8
Tel: 416 923 8839; Fax 416 923 6531
E-mail: richardgilbert@sympatico.ca

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Introduction

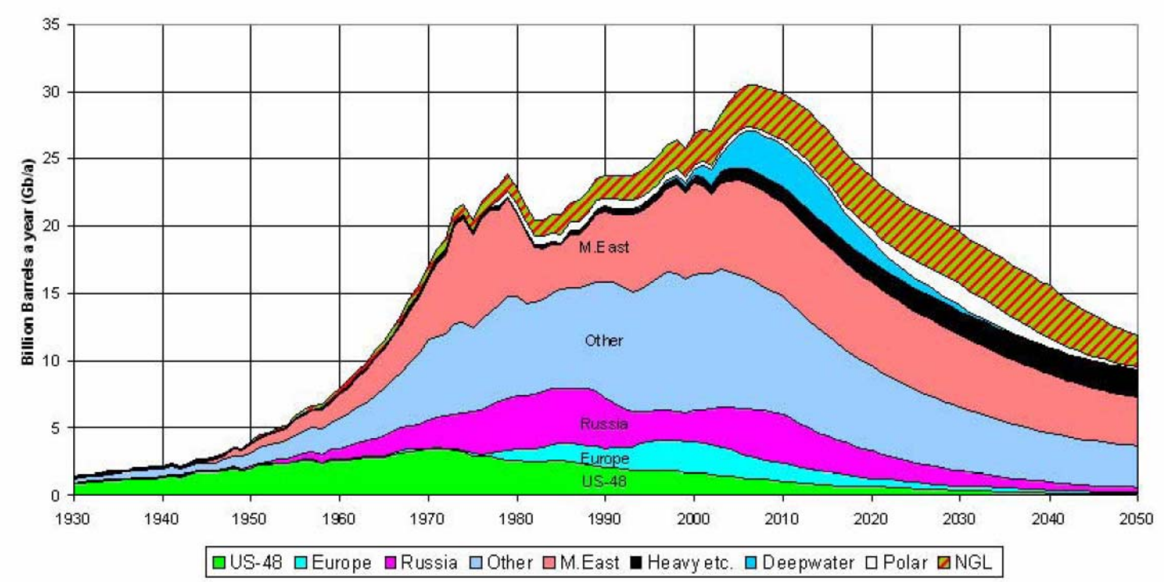
A basic dilemma for developing countries is this: Human experience suggests a strong link between transport activity and economic development, with each contributing to the other. However, provision of developed-country levels of transport activity in developing countries becomes increasingly difficult, for three reasons:

- Relative infrastructure costs can rise more quickly than the economy grows.
- Growth of awareness of pollution from transport limits options, and remediation raises costs further.
- Transport fuel prices are rising, with the prospect of larger increases.

A further factor, related to the second and third of these reasons, is the need for sustainable development. For transport, this means deploying systems and practices that do not reduce options for future generations. In particular, such transport should not cause cumulative contamination of air, land, and water; and they should not use non-renewable fuels.

Part of the problem for developing countries is that available models for growth in transport activity—and thus economic activity—all involve massive increases in road transport based on use of internal combustion engines (ICEs) fueled by oil products (chiefly gasoline and diesel fuel, and the kerosene used in jet engines). These models may be particularly problematic in relation to the above factors.

Figure 1. World production by region of regular oil and natural gas liquids, actual and estimated, billions of barrels per year, 1930-2050[2†]



Moreover, the end of cheap oil is in sight and may already be here. After several false alarms, the prospect of major constraints on the availability of transport fuels is becoming more firmly entrenched. A consensus is beginning to emerge that world *production* of oil could peak during the next two decades (see Figure 1).[1] The production peak would echo the peak in worldwide oil *discovery*, which occurred in the early 1960s (see Figure 2 on the next page).

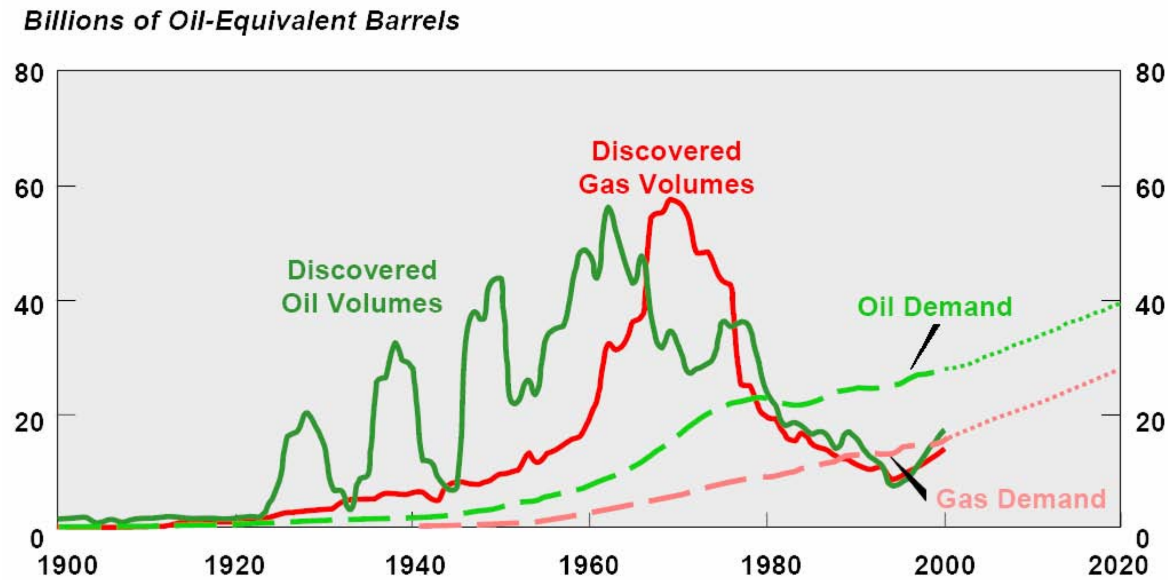
Meanwhile, potential demand for transport fuels could continue to rise, driven chiefly by growth in economic and transport activity in China and other industrializing countries,[3] resulting in sharply elevated prices.[4]

Almost every aspect of life in industrialized countries depends on the ready availability of low-cost crude oil, whose products now fuel 95 per cent of transport.[5] Notable features of the dependence are sprawling communities and long supply chains. Both will be difficult to change when oil becomes very expensive. The result could be massive economic and social disruption.

Much of the automotive industry and many governments or developed countries propose that hydrogen used in fuel cells—or even in internal combustion engines (ICEs)—will replace gasoline and diesel oil as transport fuels.[6] This scenario is unlikely because both hydrogen and fuel cells will be too expensive.

† Superscript numbers refer to reference and other notes beginning on Page 9.

Figure 2. World discovery of and demand for oil, 1900-2000, and projected potential demand until 2020[7]



Today, most hydrogen is made from natural gas. Discoveries of natural gas worldwide peaked a decade or so after discoveries of oil peaked (see Figure 2). Thus, as world production of oil is expected to peak during the next two decades, so might natural gas production peak within three decades. North American production of natural gas—the source of about 95 per cent of hydrogen produced in the U.S.[8]—appears to have already peaked,[9] resulting in large increases in wholesale and retail prices.[10] There is much natural gas in the Middle East, Russia, and elsewhere,[11] but major constraints on moving it between continents.[12] An expensive alternative is electrolysis using renewable sources of electricity.[13]

Even with sufficient low-cost hydrogen, fuel cells may well be too expensive, unreliable, and inefficient to permit their penetration as functional equivalents to ICE-powered vehicles. According to a recent analysis, “In spite of substantial R&D spending by the [U.S. Department of Energy] and industry, costs are still a factor of 10 to 20 times too expensive, these fuel cells are short of required durability, and their energy efficiency is still too low for light-duty-vehicle applications. Accordingly, the challenges of developing … fuel cells for automotive applications are large, and the solutions to overcoming these challenges are uncertain.”[14]

In any case, in an energy-constrained world it will make more sense to drive electric motors directly rather than use electricity to produce hydrogen that, via a fuel cell, is used to produce electricity. Thus, land transport systems in the 21st century could be dominated by tethered vehicles, i.e., vehicles that receive their motive energy via a rail, wire or magnetic effect than from an on-board source such as a gasoline tank or a battery. Such systems can rely entirely on renewable energy sources. They allow easy transitions among fuels, and can make strong contributions to reducing local pollution.

Tethered vehicles have three relevant advantages, discussed below: (i) they can have remarkably low energy intensities; (ii) their primary fuels can include a wide range of renewable and non-renewable sources; (iii) these primary fuels, and their associated electricity generating systems, can be readily substituted for each other, thus allowing easy transitions towards use of renewable energy; and (iv) for the most part they involve familiar, tried, tested, and available technology.

Tethered vehicles also have two disadvantages, also discussed below: (i) they are confined to routes with appropriate infrastructure (e.g., rails and wires); and (ii) they rely on continuously available, centrally provided power.

In an energy-constrained world that uses as little fossil fuel as possible, the advantages of tethered vehicles will likely be seen to greatly outweigh the disadvantages.

Thus, what is proposed here is that developing countries leapfrog over two features of the evolution of transport in developed countries. The first is the dependence on ICEs and fossil fuels. The second is the emerging commitment to transport systems fueled by hydrogen. Instead, developing countries should consider moving directly to embrace tethered systems, within and between urban regions, as the mainstays of their transport arrangements.

In the discussion that follows, the focus will be on the transport aspects of tethered systems, but the energy aspects are equally important. A fundamental question is whether sufficient electricity could be sustainably generated to support widespread tethered transport systems as well as provide for current uses. The answer seems to be ‘yes’.[15]

Energy use by tethered and other vehicles

The superior performance of tethered passenger vehicles with respect to energy use is illustrated in Table 1 on the next page, which mostly uses North American examples. In each of the three categories of vehicle, tethered vehicles show lower *operational* energy use.

Overall (primary) energy use can be much greater than operational (secondary) energy use, according to how the energy is supplied. For example, electricity produced by a combined-cycle gas turbine generator requires expenditure of about 90 per cent more primary energy in the form of generator fuel as is available in the secondary energy in the electricity.[16] Similarly, if hydrogen for a fuel cell is produced by electrolysis, the energy content of the electricity used is about 60 per cent higher than the energy content of the hydrogen produced.[17]

Table 1. Energy use in megajoules per passenger-kilometre by various modes. Tethered modes are shown in colour and italics[18]

Vehicle type	Fuel	Occupancy (pers./veh.)	Energy use (mJ/pkm)
Personal vehicles:			
SUVs, vans, etc.[19]	Gasoline	1.70	3.27
Large cars[19]	Gasoline	1.65	2.55
Small cars[19]	Gasoline	1.65	2.02
Motorcycles[19]	Gasoline	1.10	1.46
Fuel-cell car[20]	Gasoline	1.65	0.92
Hybrid electric car[21]	Hydrogen	1.65	0.90
Very small car[22]	Diesel	1.30	0.89
Personal Rapid Transit[23]	*Electricity*	*1.65*	*0.49*
Public transport between cities:			
Intercity rail (U.S.)[24]	Diesel		2.20
School bus[19]	Diesel	19.5	1.02
Intercity bus[19]	Diesel	16.8	0.90
Intercity rail (U.S.)[24]	*Electricity*		*0.64*
Public transport within cities:			
Transit bus (U.S.)[25]	Diesel	9.3	2.73
Trolleybus (U.S.)[25]	*Electricity*	*14.6*	*0.88*
Light rail (streetcar, U.S.)[25]	*Electricity*	*26.5*	*0.76*
Heavy rail (subway, U.S.)[25]	*Electricity*		*0.58*

With such conversion losses, it is important to consider the primary energy use; this is a better indicator of the energy burden. However, when the secondary energy—which provides the motive power—can be produced with little intermediate conversion, considerations of primary energy use are less important. Examples are gasoline produced from conventional oil and electricity from wind turbines.

Tethered vehicles also provide superior performance in freight transport. There are no tethered electric freight trains in North America. The comparison in Table 2 is for Finland. Not shown are tethered versions of trucks, known as ‘trolley trucks’, which like trolleybuses are powered through an overhead wire. They are used extensively in mining and other off-road operations (see Figure 3 on Page 7). Data on the comparative energy use of trolley trucks and regular trucks are not available; the difference is difference between the two is likely comparable to that shown in Table 2 for diesel and electric trains.

Table 2. Energy use by freight transport in Finland, in megajoulesper tonne-kilometre.[26]

Vehicle type	Fuel	Energy use (mJ/tkm)
Truck	Diesel	0.45
Train	Diesel	0.20
Train	*Electric*	*0.06*

The particular features of electric motors that make them more efficient than comparable internal-combustion engines are: (i) higher torque at low speeds, thus requiring less fuel use and a smaller engine; (ii) smaller engines mean less weight to carry, also meaning less fuel use; and (iii) electric drive systems can have regenerative braking—motive energy is captured when decelerating rather than lost as friction heat—again resulting in energy savings.

The low energy intensities of tethered vehicles, for passengers and freight, suggest that extensive use of them should be considered as part of the preparation for an era of energy constraints.

Tethered vehicles can use a variety of primary energy sources

Just about as important for sustainability as tethered vehicles' low energy intensity is their versatility in the use of primary energy sources. Any means of generating electricity for the grid is a primary source of energy for tethered vehicle operations. In this way, wind, sun (thermal and photoelectric), tide, falling water, nuclear fission, and combustion of fossil fuels and biofuels can all be energy sources for tethered vehicles.

As we move towards an energy future whose only certainty may be reduced reliance on fossil fuels, the ability to power transport by a wide variety of sources will be advantageous. Moreover, electricity is the most convenient energy currency of many sustainable primary sources, including wind, sun (photoelectric), tide, and falling water.

Tethered vehicle technology is readily available

Tethered electric vehicles have been in practical use for at least 120 years.[27] There were streetcars on Canadian streets before there were automobiles.[28] There has been continuous development of the technology as adoption of these modes has spread throughout the world, and as technical requirements have been enhanced (e.g., for high-speed trains).

Building on this well-established technology, there are many opportunities for further enhancement, especially in the matter of personal rapid transit (PRT, noted in Table 1). Because PRT could provide a convenient, affordable alternative to automobile use in low-density areas, it offers the opportunity to address what in developed countries may be seen as be the most intractable of transport challenges. A PRT system could even provide for individual ownership of automobiles equipped to spend most journeys in tethered mode but the first and last few kilometres of each trip in battery mode.

Figure 3. Trolley truck operating at the Quebec Cartier iron ore mine, Lac Jeannine, 1970s.[29]

Provision for such dual-mode operation may be an unnecessary sophistication in places where automobile ownership is not widespread.

Another major challenge concerns road freight transport, the fastest growing source of energy use and greenhouse gas emissions in most countries. It's possible to conceive of technological development that would allow any truck, and even any road vehicle, to draw motive power from overhead wires, replacing some of it during braking.

Tethered vehicles are restricted to powered routes

The most serious disadvantage of tethered vehicles is their infrastructure requirements. At a minimum, they require wires above existing roads, and the means to power them. According to the type of vehicle, they could also require new rails or other guideways.

A similar challenge confronted automobiles 100 years ago. They were mostly confined to summer travel on roads within urban areas. In 1910, the only paved highway in Canada, for example, was a 16-kilometre stretch from Montreal to Ste.-Rose. Present levels of route flexibility took many years to develop. Indeed, an automobile was not driven across Canada until 1946, and the Trans-Canada Highway was not completed until the 1960s.[30] Today's automobiles and trucks may be even more confined to laid-out roads than those of a century ago, but the road system is extensive, reaching to most parts of southern Canada.

Widespread adoption of tethered vehicles for the next transport revolution could well involve continued use of the present road system, with the addition of powered overhead wires that can be shared by all. However, vehicles run more efficiently on rails or tracks than on roads, and energy constraints may favour trains and other vehicles confined to special-purpose rights-of-way.

Tethered vehicles require continuously available, centrally provided power

Toronto's streetcars and subway trains stopped during the major blackout that affected eastern North America on August 14, 2003, but cars and trucks kept on rolling, at least for a time. Then they were stopped in traffic jams caused by non-functioning traffic signals and by line-ups at non-functioning gas stations.

It is nevertheless true that cars and trucks have some additional resilience compared with tethered systems because they carry their own fuel. However, both depend ultimately on heavily centralized systems of energy distribution.

Greater dependence on tethered transport systems would stimulate designs for greater resilience involving more distributed production and greater redundancy. These would in any case be likely features of a more sustainable system of energy supply.

Leapfrogging developed countries' transport strategies

This paper's advice is that developing countries leapfrog over developed countries' attachments to ICEs and to replacing ICEs with fuel cells by focusing now on installing tethered transport systems. Then, when fuel cells and the hydrogen economy prove unworkable—for transport—perhaps in a decade or two—today's developing countries will have better transport systems than today's developed countries, and the latter will have much to learn from the former.

The primary impetus for such leapfrogging would be conviction as to the imminence of early severe energy constraints, particularly for transport fuels. Developing countries need to assess for themselves whether the world oil and natural gas production will peak soon. They may be in a better position than developed countries to make such an assessment as they are for the most part not blinkered by experience of ever-available low-cost fuels.

There are other reasons for eschewing the transport strategies of developed countries. Not the least is avoidance of imports of fuels and vehicles, and of the external costs associated with widespread use of ICE vehicles. Moreover, other things being equal, a transport system based on independently mobile vehicles could occupy a larger share of GDP than one relying more on collective transport, without necessarily providing overall a higher level of transport service.[31]

End Notes

[1] The emerging consensus is most strongly illustrated in International Energy Agency, *World Energy Outlook 2004* (IEA, Paris, France, 2004). For an examination of this point, see Aleklett K, *IEA accepts peak oil: An analysis of Chapter 3 of the* World Energy Outlook 2004, available at the Web site below (Web site of the Uppsala Hydrocarbon Depletion Group).
1. http://www.peakoil.net/uhdsg/weo2004/TheUppsalaCode.html. Accessed December 19, 2004.

[2] Figure 1 was taken from Figure 20 of the paper by Aleklett detailed in Note 1. The figure suggests that production of liquid hydrocarbons suitable for conversion into transport fuels will peak before 2010. Some estimates point to earlier peaks, e.g., in 2005, as projected in Deffeyes KS, *Hubbert's Peak: The Impending World Oil Shortage.* Princeton University Press, 2001. Others point to later peaks, e.g., in 2018-2023, as projected in White N, Thompson M, Barwise T, Understanding the thermal evolution of deep-water continental margins, *Nature*, 426:6964, 324-333, 2003. Extreme among the projections of later production peaks are those of the U.S. Energy Information Administration (EIA), which suggests production will continue rising beyond 2025 (*International Energy Outlook 2004*, Washington DC, 2004, available at the URL below) and, until recently, those of the International Energy Agency (IEA), which suggests oil production will continue rising until 2030 (*Energy to 2050: Scenarios for a Sustainable Future*. IEA, Paris, France, 2003). As noted in the paper by Aleklett, the IEA now accepts that the peak in oil production could come by 2015 or before. Energy constraints will arise from potential demand running ahead of actual production of liquid hydrocarbons resulting in high prices, *not* from depletion of all available oil. Put another way: "The world is not about to run out of hydrocarbons, and perhaps it is not going to run out of oil from unconventional sources any time soon. What will be difficult to obtain is cheap petroleum, because what is left is an enormous amount of low-grade hydrocarbons, which are likely to be much more expensive financially, energetically, politically and especially environmentally." (Hall C and four others, Hydrocarbons and the evolution of human culture. *Nature*, 426:6964, 318-322, 2003).
1. http://www.eia.doe.gov/oiaf/ieo/. Accessed December 19, 2004.

[3] According to the June 2004 issue of the *BP Statistical Review of World Energy*, available at the first URL below, China passed Japan in 2002 to become the world's second major user of oil after the U.S. (although in 2003 using only 31% of U.S. consumption). Over the decade 1993-2003, use of oil in China increased by 103%, an annual rate of 7.3%. Use of oil in Canada, the U.S., the European Union, and Japan had increased respectively by 26%, 16%, 7%, and 0% over these 10 years. According to the table on Page 14 of the most recent *Monthly Oil Market Report* of the International Energy Agency (December 10, 2004, available at the second URL below), China's net imports of oil and oil products and feedstocks during the first nine months of 2004 were 42% above those for the equivalent period in 2003, perhaps reflecting a plateauing or even a peaking of indigenous oil production as extraction reaches the mid-point of ultimately recoverable reserves. (For further discussion of this last point see Newsletter No. 40 of the Association for the Study of Peak Oil and Gas, April 2004, available at the third URL below.)
1. http://www.bp.com/subsection.do?categoryId=95&contentId=2006480. Accessed December 19, 2004.
2. http://omrpublic.iea.org/currentissues/full.pdf. Accessed December 20, 2004.
3. http://www.asponews.org/docs/Newsletter40.pdf. Accessed December 22, 2004.

[4] At the time of writing (December 2004), the price of crude oil (West Texas Intermediate) is close to US$45 per barrel, about 40% above the price 12 months earlier. In December 1998 it was near US$10 per barrel. (See, for example, the URL below.)
1. http://www.oilnergy.com/1onymex.htm#since20, Accessed December 22, 2004.

[5] According to Page 431 of the first source detailed in Note 1, 95.1% of the energy used for motorized transport worldwide in 2002 came from oil, i.e., 1,737 out of 1,827 million tonnes of oil equivalent.

[6] According to the International Energy Agency, "In the long term, perhaps the most promising path for virtually eliminating the direct use of petroleum fuels … is the hydrogen fuel cell. Once all vehicles operate on hydrogen fuels, they will be potentially renewably fuelled (if a renewable source of hydrogen is developed), and will produce water as their only emission." (Pages 168-169 of *Towards a Sustainable*

Energy Future, IEA, Paris, France, 2001). In January 2003, U.S. President George Bush announced the FreedomCAR and Fuel Initiative "to reverse America's growing dependence on foreign oil by developing the technology needed for commercially viable hydrogen-powered fuel cells", detailed at the first URL below. Hydrogen can be used as fuel for internal combustion engines, but its use in fuel cells is said to offer "significantly greater potential" (see the second URL below).
1. http://www.eere.energy.gov/hydrogenandfuelcells/presidents_initiative.html. Accessed December 20, 2004.
2. http://www.initiative-brennstoffzelle.de/ibz/live/nachrichten/show.php3?id=98&p=0&nodeid=0&art=e. Accessed December 20, 2004.

[7] Figure 2 is from Slide 4 of a presentation by Harry J. Longwell, Executive VP, Exxon Mobil Corporation at the Offshore Technology Conference, Houston, Texas, May 7, 2002, available at the first URL below. Figure 2 shows oil discoveries only until 2000 and may suggest they were then on the rise again after a long decline. Data for subsequent years show this is not the case. According to Smith MR, *World Oil Supply Report*, 3rd edition, Douglas-Westwood Ltd., 2004, as reported in Anon, Study: World oil forecast beset with reserves shortfalls. *Oil & Gas Journal*, April 12, 2004, discoveries in 2000, 2001, and 2002 were respectively 13.05, 4.02, and 3.34 billion barrels. According to energy consultants IHS, 2003 may be the first year since the beginning of the modern oil industry in which there were no large oil discoveries at all (see the news release of their report at the second URL below). The results for 2003 have been described by the editor of *Petroleum Review* as "little short of horrifying".
1. http://www.exxonmobileurope.com/Corporate/Newsroom/SpchsIntvws/Corp_NR_SpchIntrvw_Houston_070502.asp. Accessed December 19, 2004.
2. http://www.ihsenergy.com/company/press/pressreleases/arc2004/pr_011204-activity03.jsp. Accessed December 20, 2004.

[8] According to Amory Lovins, *Twenty Hydrogen Myths* (Rocky Mountain Institute, 2003, at the URL below), "U.S. hydrogen production is at least one-fifth and probably nearer one-third of the world total, is equivalent to ~1.8% of total U.S. energy consumption, and comes ~95% from natural gas at ~99% purity from steam reforming and associated cleanup processing".
1. http://www.rmi.org/images/other/Energy/E03-05_20HydrogenMyths.pdf. Accessed December 20, 2004.

[9] For an informed view that North American natural gas production may have already peaked, see the presentation by Matthew Simmons, *The Natural Gas Riddle: Why Are Prices So High? Is a Serious Crisis Underway?* at the mini-conference of the International Association for Energy Economics, Houston, Texas, December 11, 2003, available at the URL below.
1. http://www.simmonsco-intl.com/files/IAEE%20Mini%20Conf.pdf. Accessed December 20, 2004.

[10] The Alberta Gas Reference Price increased almost three-fold between October 1988 and October 2004, from $1.86 to $5.29 per gigajoule (see the URL below).
1. http://www.energy.gov.ab.ca/gmd/gas/monthlyref.asp. Accessed December 20, 2004.

[11] According to the first source detailed in Note 3, North America was responsible for 24% of world natural gas consumption in 2003 but had only 3% of proven natural gas reserves. The Middle East and Russia had respectively 41% and 27% of proven reserves.

[12] Natural gas can be economically shipped between continents as liquefied natural gas (LNG) when the wholesale natural gas price is above about U.S.$3.50 per gigajoule (see the chart on Page 67 of *International Energy Outlook 2004*, detailed in Note 2). Three difficulties impede rapid expansion of LNG imports: (i) a shortage of vessels designed to carry LNG; (ii) a shortage of terminals designed to receive LNG; and (iii) movement of LNG is regarded as hazardous. On the last point consider the following from Powers B, *Assessment of Potential Risk Associated with Location of LNG Receiving Terminal Adjacent to Bajamar and Feasible Alternative Locations*, at the first URL below: "The US Coast Guard requires a two-mile moving safety zone around each LNG tanker that enters Boston Harbor, and shuts down Boston's Logan Airport as the LNG tanker passes by. … These extraordinary precautions are taken out of concern for spectacular destructive potential of the fire and/or explosion that might result from a LNG tank rupture." Also of concern is terrorist action. A recent report done for the U.S Department of Energy

sets out some of the risks and concerns. It was Hightower M and nine others, *Guidance on risk analysis and safety implications of a large liquefied natural gas (LNG) spill over water*. Sandia National Laboratoris, Albuquerque, New Mexico, December 2004, available at the second URL below. The report has been criticized as being selective by Raines B, Finch B, Scientists say LNG review is missing critical studies. *Mobile Register*, December 23, 2004, available at the third URL below.
1. http://www.borderpowerplants.org/pdf_docs/lng_position_paper_june2002_english.pdf. Accessed December 23, 2004.
2. http://www.fe.doe.gov/programs/oilgas/storage/lng/sandia_lng_1204.pdf. Accessed December 23, 2004.
3. http://www.wildcalifornia.org/pages/page-114. Accessed December 23, 2004.

[13] According to Page 119 of Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. (Washington DC, National Academies Press, 2004), available at the URL below, the current cost of hydrogen from electrolysis is four times or more the cost of hydrogen produced from natural gas, and with anticipated future technologies will continue to be at least twice as expensive as other means of production.
1. http://www.nap.edu/openbook/0309091632/html/119.html. Accessed December 20, 2004.

[14] The quote is from Page 119 of the source detailed in Note 13. See also Demirdöven N, Deutch J, Hybrid cars now, fuel cells later. *Science, 305*, 974-976, 2004.

[15] For an assessment see, for example, Czisch G, *Global Renewable Energy Potential*. ISET, University of Kassel, Germany, available at the URL below.
1. http://www.iset.uni-kassel.de/abt/w3-w/folien/magdeb030901/. Accessed December 21, 2004.

[16] For generator efficiency see, for example, Wei A, *Technologies for Next Generation Turbine Systems*. Presentation at the Turbine Power Systems Conference and Condition Monitoring Workshop, Galveston, Texas, February 2002, available at the URL below.
1. http://www.netl.doe.gov/publications/proceedings/02/turbines/wei.pdf. Accessed December 23, 2004.

[17] For the efficiency of electrolysis, see Page 171 of the source detailed in Note 13

[18] The sources for the estimates in Table 1 are in the corresponding end notes. The table shows *end* or secondary energy. As noted in the text, primary or full-cycle energy use can be much greater.

[19] The data in this row are derived from the electronic version of *Energy Use Data Handbook* (Ottawa, Ontario, Natural Resources Canada, June 2004), available at the URL below.
1. http://oee.nrcan.gc.ca/neud/dpa/handbook_tables.cfm?Text=N&Print View=N. Accessed December 23, 2004.

[20] The fuel-cell-car data are for the 2004 Honda FCX subcompact, as posted by the U.S. Department of Energy at the URL below.
1. http://www.fueleconomy.gov/feg/fcv_sbs.shtml. Accessed December 23, 2004.

[21] The data for a hybrid gasoline-electric car are those for the 2004 Toyota Prius midsize car, as posted by the U.S. Department of Energy at the URL below.
1. http://www.fueleconomy.gov/feg/hybrid_sbs.shtml. Accessed December 23, 2004.

[22] The data for the 'very small car' are those for Volkswagen's Lupo 3L, a two-seater-plus diesel car available only in Europe and described by the manufacturer as the "first 3L vehicle in production" (see Klaus-Peter Schindler, *The future of the Diesel engine in passenger cars*. Presentation at the 7th Diesel Engine Emissions Reduction Workshop, Portsmouth, Virginia, August 2001, at the first URL below). Manufacturer's energy-use data are given here, i.e., 2.99 litres/100 km, equivalent to 0.89 mJ/pkm for an occupancy of 1.30 (the present author's estimate). In Slide 10 of the cited presentation, a rate of 0.75 mJ/pkm is given for "average rate of occupation" "in urban traffic under 75 km", which suggests an average occupancy of 1.54 or higher. Testing of the Lupo 3L by Transport Canada indicated highway fuel use of 3L/100 km and city fuel use of 3.8L/100 km (*Advanced Technology Vehicles Program, 2001-2002 Annual Report*, Road Safety and Motor Vehicle Regulation, Transport Canada, January 2003, at the second

URL below).
1. http://www.osti.gov/fcvt/deer2001/schindler.pdf. Accessed December 23, 2004.
2. http://www.tc.gc.ca/roadsafety/atvpgm/reports/annual/atvp0102.pdf. Accessed December 23, 2004

[23] Personal Rapid Transit (PRT) is a generic term for concept systems comprising fully automated small vehicles carrying 1-6 passengers running on guideways at, above or below ground, providing direct origin-to-destination service. A useful review of these and other innovative technologies can be found at a Web site maintained by Jerry Schnieder of the University of Washington, at the URL below. The energy use shown in Table 1 represents the average of several developers' estimates.
1. http://faculty.washington.edu/jbs/itrans/. Accessed December 23, 2004.

[24] Amtrak's Northeast corridor is the only electrified part of the intercity rail system in North America. About 2.63 billion passenger-kilometres (pkm) were performed in this corridor in 2000 and about 6.34 billion pkm in the rest of the U.S. system (this author's estimates from various sources, notably Report No. GAO/RCED-96-144 by the U.S. General Accounting Office, *Northeast Rail Corridor: Information on Users, Funding Sources, and Expenditures*, 1996, at the first URL below, and Table 9.12 of Davis SC, Diegel SW, *Transportation Energy Data Book 23*, Oak Ridge Tennessee: Oak Ridge National Laboratory, 2003, at the second URL below). According to Table A.16 of the second source, 470,170,000 kilowatt-hours of electricity and 94,968,000 U.S. gallons of diesel fuel were used respectively to provide this service.
1. http://www.gao.gov/archive/1996/rc96144.pdf. Accessed December 23, 2004.
2. http://www-cta.ornl.gov/data. Accessed December 23, 2004.

[25] The data in this row are derived from data on U.S. systems provided by the American Public Transportation Association (APTA), available at the URL below.
1. http://www.apta.com/research/stats/. Accessed December 23, 2004.

[26] The freight transport data in Table 2 are from the source at the URL below. In Finland, electric freight trains appear to use less than one third of the operational energy per tonne-kilometre (tkm) used by comparable diesel freight trains, which in turn use less than half of the energy used by trucks. Note that the report energy use by Finnish trucks (0.45 mJ/tkm) is very much lower than the use estimated even for heavy Canadian trucks in the source detailed in Note 19 (2.41 mJ/tkm). However, the Finnish and Canadian sources present similar estimates of energy use by diesel freight trains (respectively 0.20 and 0.25 mJ/tkm).
1. http://www.ecotraffic.se/pdf/et.pdf. Accessed Feb. 7, 2004.

[27] See, for example, the URL below.
1. http://mikes.railhistory.railfan.net/r066.html. Accessed December 23, 2004.

[28] Filey M, Howard R, Weyerstrahs H, "*Passengers Must Not ride on Fenders*", Toronto, Ontario, Green Tree Publishing Co., 1974).

[29] The trolley truck photo is at the URL below.
1. http://hutnyak.com/Trolley/trolleyphotos.html. Accessed December 23, 2004.

[30] Nichol J, *The All-Red Route* (Toronto, Ontario, McArthur and Co., 1999).

[31] The first part of this assertion is intuitively obvious, although requires substantiation. The second part—concerning a higher level of transport service—depends, for example, on comparing Toronto with Hong Kong. In relatively sprawling Toronto, where most journeys are made by car, it's usually hard to fit in more than three business meetings a day. In compact Hong Kong, where the overwhelming majority of motorized trips are made by public transport, participating in twice as many meetings per day is entirely possible. (This is not to say that meeting frequency is a good index of economic efficiency, but only to illustrate what is possible.)