GCEP

STANFORD UNIVERSITY
Global Climate & Energy Project


Technical Assessment Report

An Assessment of Advanced Transportation Research Opportunities

GCEP Energy Assessment Analysis
Spring, 2006

Abstract

Fundamental research can play a role in reducing greenhouse gas emissions associated with growing global transportation energy use by enabling technologies that either significantly reduce the energy requirement of transportation or decouple vehicle energy use and emissions. Current research toward these ends is summarized, not including research areas outlined in other GCEP assessment reports with relevance to transportation such as hydrogen, combustion, and biomass. Reducing the energy requirement for transportation may be accomplished by reducing vehicle mass, smoothing the operational speed profile, and reducing viscous and contact friction. Specific technical challenges in these areas include the low-cost production of high-strength, low-weight materials and the technical foundation to enable automated vehicles. Fuel chains with low net greenhouse gas emissions include portable storage of low-carbon electricity and carbon-based fuels synthesized from low-carbon energy. Significant technical challenges in this area include developing batteries with high energy density and stability and developing classes of low-cost catalysts capable of efficiently converting low-carbon energy into and out of forms amenable for portable storage.

Issued by the Global Climate and Energy Project http://gcep.stanford.edu

Table of Contents

Foreword

This report is one of a series of assessments on various areas of the energy landscape prepared by GCEP staff. The assessments are intended to provide an introduction to the energy area as well as context for future fundamental research activity towards reducing greenhouse gas emissions. By examining the goals and potential of the energy transformations in question as well as the current progress and research towards these ends, the assessments take a step toward elucidating the most promising areas for future research. This report, produced by GCEP Energy Analysis staff, was written by Wes Hermann with contributions from Paolo Bosshard, Emilie Hung, Rebecca Hunt, and AJ Simon. Please address all correspondence to gcep@stanford.edu.

Introduction

Moving people and goods is an increasingly important aspect of human society. We commute to places of work and recreation and ship goods and materials to destinations both local and global. Mobility, a measure of the distance a person travels in a given period of time, has increased markedly over the last several decades and is expected to triple by 2050 [1]. Since mobility has been shown to be related to wealth, a large portion of this growth is expected to come from developing countries as the population rapidly transitions to an industrial economy as illustrated by Figure 1. The amount of time a person devotes to travel is approximately constant across all countries and income levels, but the distance a person travels is correlated with income. This leads to an increase in travel speed along with wealth. There has been a significant increase in demand for high speed transportation systems such as air and high speed rail over the past several decades and this trend is expected to continue in the future.

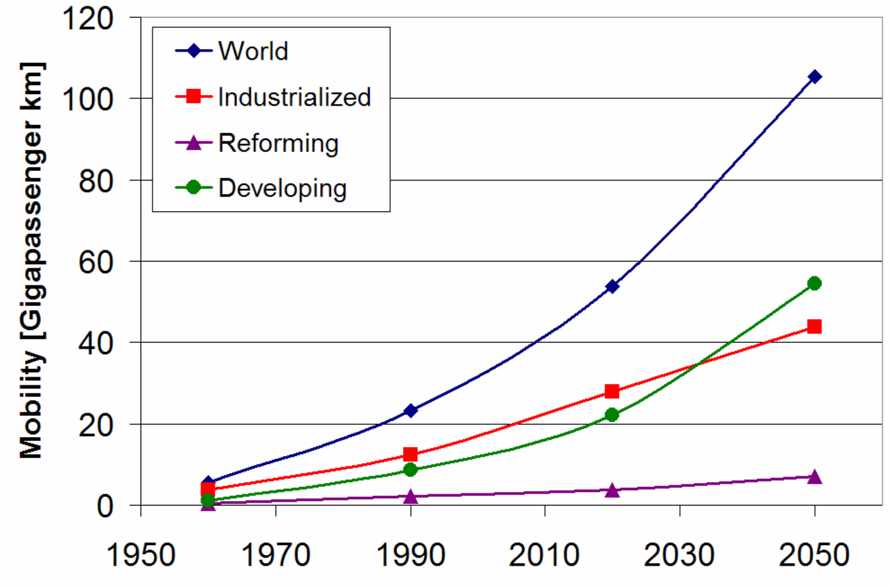

Figure 1: Mobility history and projections by country classification [1]

A large and growing fraction of global energy use and greenhouse gas emissions is directly associated with transportation. Worldwide, 2.5 TW are used for transportation and CO_2 emissions from the combustion of carbon-based fuels in transportation applications are 24% of global energy-related emissions. Transportation's fraction of global greenhouse gas emissions is expected to approach one third in the coming decades [2,3]. In conjunction with the amount of energy used for transportation energy services, the net carbon intensity of the energy carriers determines the total greenhouse gas emissions. The current global transportation system is dominated by the use of fossil petroleum, as illustrated in Figure 2, due to its high energy density and ease of storage and handling. However, a carbon intensity of about 20 gC/MJ makes this fuel undesirable as part of a low carbon emissions energy future without radical changes in the transportation energy requirement.

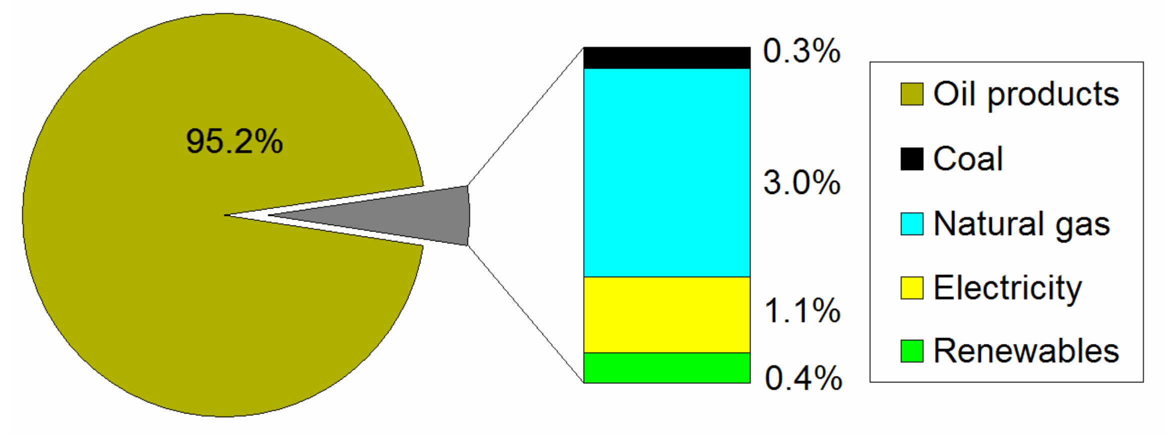

Figure 2: Global transportation energy consumption by energy carrier [4]

Energy used for transportation has a variety of specific applications that vary in cargo and speed. In the United States, for which detailed transportation statistics are readily available, about two thirds of energy use in the transportation sector is a result of transporting people, mostly in light duty vehicles, and one third results from moving goods and material. This energy use is distributed among a range of transportation modes as illustrated in Figure 3. Light duty vehicles account for over 85% of energy use for passenger transport in the United States.

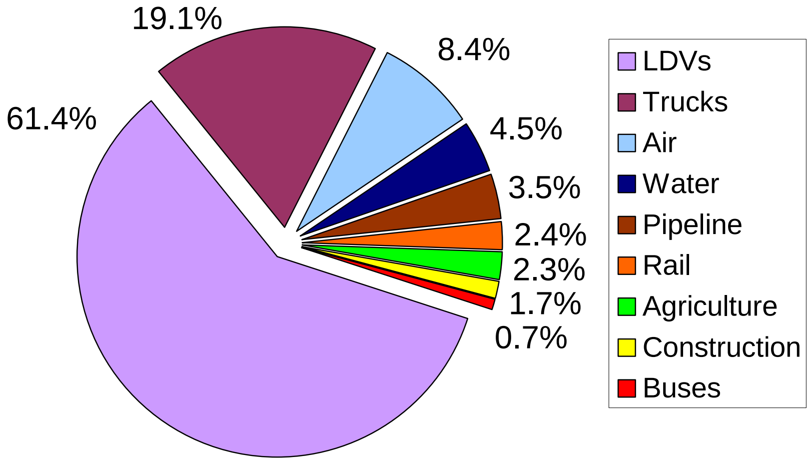

Figure 3: Percentage of United States transportation energy use by transport mode, 2002 [4]

Many of the factors that determine the structure and composition of transportation systems are non-technological. However, new technology options that either enable low net CO_2 transportation fuel cycles or greatly decrease the energy use of transportation vehicles could help reduce the contribution of the transportation sector to the increasing concentration of greenhouse gases in the atmosphere. Switching vehicles to low net greenhouse gas emissions fuels has the potential to nearly eliminate greenhouse gas emissions from transportation. Alternatively, decreasing vehicle energy requirement would serve both to reduce the aggregate amount of emissions as well as enable certain alternative fuels that have limitations such as low energy storage density or, in the case of biofuels, finite amounts of land available for harvesting fuel. Both will likely be required to meet the demand for energy services and the environmental goals of this century. This report outlines the potential for improvement in fuel cycle greenhouse gas intensity and vehicle energy use and provides a non-comprehensive summary of current research efforts toward these goals. Since the areas of biofuels, advanced combustion, and hydrogen production, storage and use are or will be covered in other GCEP assessments, they are not addressed in this report. The results are intended to provide perspective and guidance for future research aiming to enable technology options that could have a major impact on transportation greenhouse gas emissions.

Part I: Propulsive Energy Use in Transportation

The amount of energy required to transport goods or people is directly proportional to the amount of greenhouse gases released for a fuel cycle of a given carbon intensity. New technology options have the potential to significantly decrease vehicle energy use. While there are many energy conversions along a fuel chain from resource to dissipation as heat, this section will examine the factors contributing to the final, propulsive energy requirement of transportation vehicles and summarize current research in several areas that could help improve these factors.

The energy efficiency of transportation, an energy service, is fundamentally different from the efficiency of most other energy conversions. Theoretically, zero work is required to move an object or person from one location to another at the same altitude. This suggests that if any work is expended to accomplish this goal, the efficiency, work accomplished over work expended, is zero. However, practical transportation vehicles usually move through viscous fluids and/or are in constant contact with the ground. These interactions apply loads on vehicles that are dependent on speed, mass, and other vehicle characteristics. Because of this special nature of the transportation energy service, it is more useful to quantify and compare the propulsive energy requirement of a transport vehicle or system in terms of mechanical energy expended per unit distance and cargo.

Improving the various vehicle characteristics and operating conditions that determine the applied loads can reduce the propulsive energy requirement of a vehicle. The impacts of improving many of these factors are interrelated. For example, the propulsive energy requirement of a vehicle moving at constant speed is less sensitive to its own mass than a vehicle that makes many stops and starts, and a vehicle with an exceptional kinetic energy recovery system is less sensitive to both mass and speed profile.

A simple model of vehicle propulsive energy requirement can illustrate the influence of various vehicle factors and serve as a starting place for determining which technology options could have the greatest impact on energy use. Figure 4 illustrates the marginal sensitivity of the propulsive energy requirement of various vehicle types to changes in the mass, speed profile, rolling resistance, and aerodynamic drag. The numerical labels represent the ratio of percentage propulsive energy requirement improvement to percentage variations from the nominal value for the factor for a given run of the model. The assumptions and methodology of this model are summarized in Appendix A. Each vehicle type has varying sensitivity to the four factors considered. As expected, modes experiencing a large amount of stopping and starting are more sensitive to vehicle mass, while higher speed modes are more sensitive to factors determining aerodynamic drag. This suggests that both lightweight materials and technologies that would allow for a smoother speed profile could have a significant effect on urban vehicle propulsive energy requirement, while increased aerodynamics or lower fluid density would significantly benefit higher speed and longer distance modes.

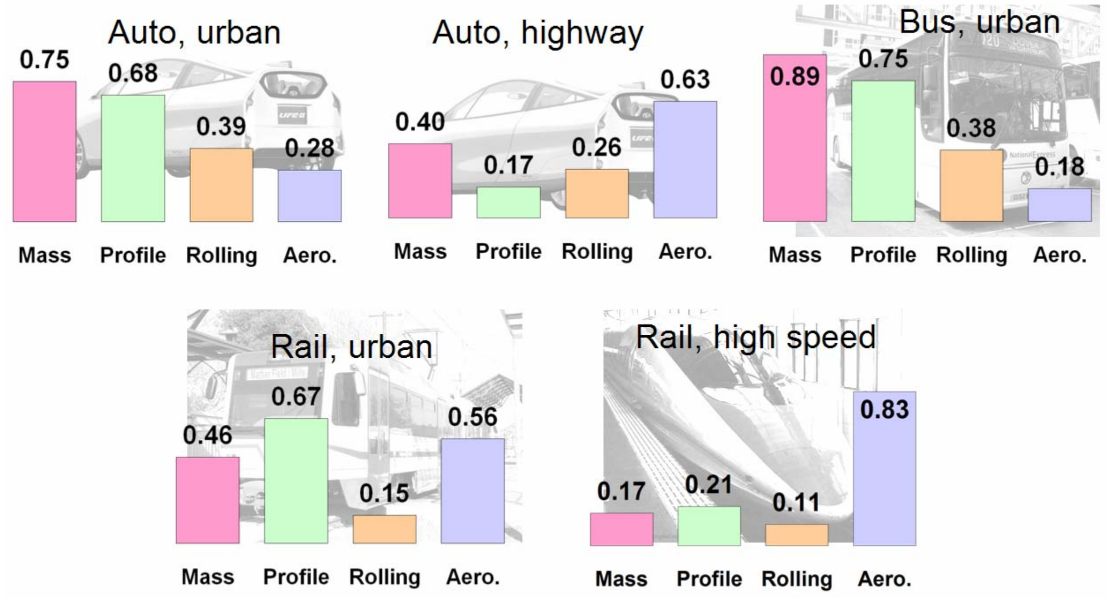

Figure 4: Sensitivity of propulsive energy requirement to vehicle factors for various modes

While Figure 4 illustrates an example of marginal sensitivity of current modes, Table 1 provides extreme examples of the potential for propulsive energy requirement reduction if various vehicle factors are idealized. While dramatic improvements in individual vehicle factors would lead to significant reductions in propulsive energy requirement, combinations of vehicle factor improvements, for example, levitated bundles of goods traveling in a low pressure enclosure, could lead to transportation systems that consume orders of magnitude less energy than today's systems. Since, unlike other energy services, zero work is theoretically required to move a person or object at constant altitude, improvements provided by new technical options have the long-term potential to decrease energy consumption for transportation by an order of magnitude or more.

Table 1: Propulsive energy use reduction factor relative to a nominal regenerative braking vehicle

	Auto, urban	Auto, highway	Bus, urban	Rail, urban	Rail, high speed
Zero vehicle mass	2.8	1.4	4.2	1.6	1.1
Smooth speed profile	1.8	1.1	2.1	1.8	1.2
No rolling friction	1.6	1.3	1.6	1.2	1.1
Vacuum	1.4	2.3	1.2	2.4	14
Perfect KE recovery	1.3	1.1	1.6	1.3	1.0
Vacuum and no rolling friction	2.8	5.8	2.2	3.9	140

Mass reduction

The central importance of vehicle mass to the propulsive energy requirement of current vehicles at urban speeds suggests that technology options enabling relatively lightweight transportation systems could have a major impact on the energy use and therefore greenhouse gas emissions associated with transportation.

Since the energy service of transportation is moving goods or people of a given mass, a technical approach to transportation mass reduction should focus on the vehicle that carries this cargo, not the cargo itself. Different transportation systems have varying ratios of maximum cargo to gross moving mass, or mass efficiency, as illustrated in Figure 5. In most cases, freight transportation systems are already quite mass efficient and would not benefit from lighter vehicles to the extent that is necessary to significantly reduce transportation energy requirements. Passenger transport, however, often has a mass efficiency below 20%. Doubling the mass efficiency of passenger transport is technically possible and could have a significant impact on energy use. One technical approach to this challenge is to replace conventional transportation vehicle materials such as steel with higher performance materials such as lighter metals or low-cost composites.

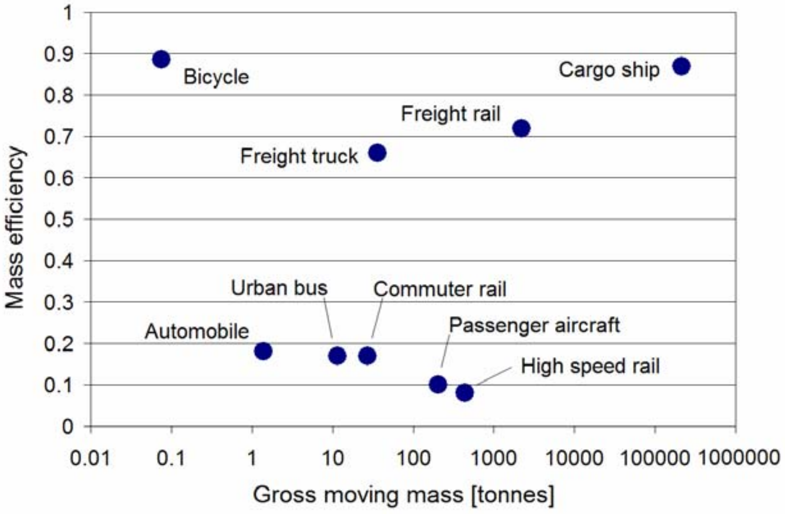

Figure 5: Cargo mass to gross vehicle mass ratio for various transportation modes

In transportation applications that already place a high premium on vehicle mass such as aircraft, higher performance materials are already used, though currently at high cost. Figure 6 illustrates the breakdown by weight for a modern aircraft and a modern automobile. The weighted average specific strength of the aircraft's structural material is over five times that of the automobile. Research could lead to new high performance materials or decrease the cost of present lightweight materials such that they are more readily available on a large scale.

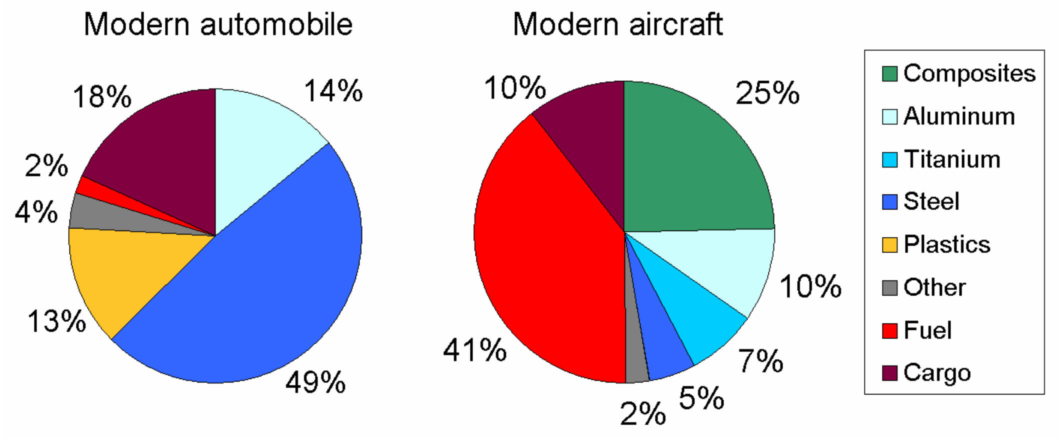

Figure 6: Automobile and aircraft mass breakdowns by material [6,7]

While there are many technical factors that determine the best material choice for vehicle applications including fatigue properties, corrosion resistance, directionality, and cost, two useful measures of the mechanical properties of structural materials in transportation applications are specific yield strength and specific impact energy absorption. An approximate representation of these properties for selected structural materials is provided in Figure 7. The strong carbon-carbon bonds composing carbon nanotubes and the graphitic structures of carbon fibers make them effective structural elements in a composite system. The small-scale deformable structure of composites can aid in energy absorption. A range values for proposed carbon nanotube polymer composites is represented by a dashed line to reflect the speculative nature of these estimates.

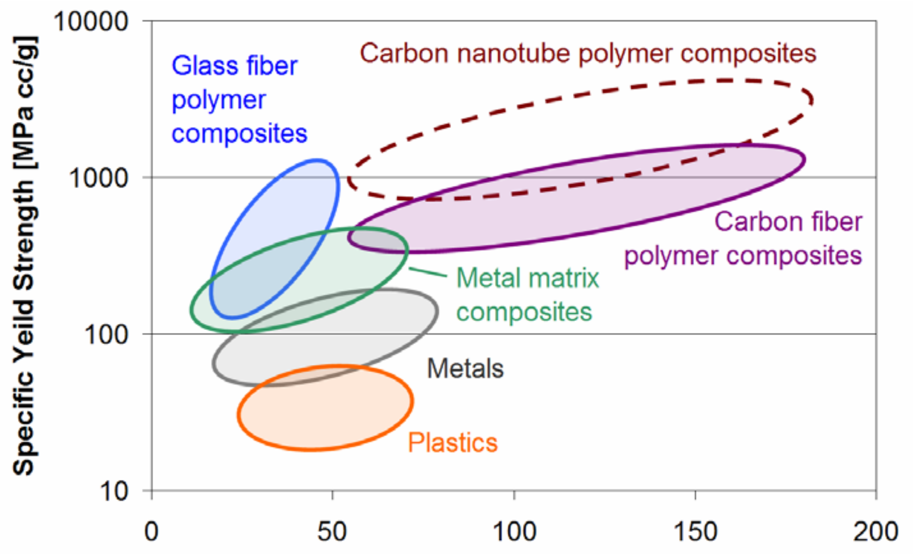

Figure 7: Mechanical properties of selected vehicle structural materials [6,8-15]

Metals and plastics already present in many transportation applications in various forms could be replaced by improved formulations including lighter weight alloys or higher strength polymers. Magnesium and aluminum have higher strength per unit weight than steel. Advanced plastics could replace heavier vehicle components by increased functionalization or significantly higher impact toughness and strength [16].

While improvements in metals and plastics could help achieve significant weight savings, higher performance materials such as composites may be needed to achieve the degree of mass reduction necessary for a major impact on transportation energy requirement. Fiber reinforced composites utilize high strength fibers embedded in a matrix. The matrix can consist of a variety of materials including metal or an organic polymer such as an epoxy. Transferring loads to the fibers can increase strength and stiffness and the interfacial movement of the fibers relative to the matrix can influence energy absorption.

Metal matrix composites (MMCs) utilize either fibers or embedded particles, increasing strength and reducing density relative to pure metal alloys. However, recent research suggests that these additives have a neutral or even detrimental effect on toughness and energy absorption [13,14]. Further study on the fundamentals of MMC interfacial bonding may lead to improvement in this respect.

Though glass fiber composites are widely used, higher performance carbon fiber composites are the subject of much ongoing research [17]. Carbon fibers are essentially complex strands of interconnected graphite sheets [18]. The theoretical tensile strength of a carbon fiber is over 30 GPa, but current fiber properties rarely exceed 3 GPa. Combining carbon fibers with a polymer matrix allows a material with macroscopic properties reflecting both the high strength of individual carbon fibers and bending and impact energy absorption associated with the interfacial movement between the fibers and the matrix.

Longer term research hopes to adopt the exceptional properties of carbon nanotubes to significantly increase the performance of polymer composites [17]. While carbon fibers have relatively active surfaces due to the edges of the graphite layers, carbon nanotubes are atomically smooth except at their ends. This makes bonding between the structural fiber and polymer matrix difficult. Some research groups are exploring the functionalization of carbon nanotube surfaces in order to engineer the bonding between the nanotube and the polymer matrix [19]. Optimal bonding would allow the nanotube to carry structural load while permitting slipping inside the matrix to increase the macroscopic toughness and energy absorption of the composite.

Speed profile leveling

Another important factor that determines propulsive energy requirement is the degree of accelerations and decelerations the vehicle will encounter, or the speed profile during operation. As previously noted, the energy requirement associated with this factor is closely coupled with the vehicle mass and the efficiency of any kinetic energy recovery system. While there are many non-technological factors that influence the speed profile of a vehicle, any technology that could help enable a smoother speed profile could have a large impact of efficiency [20].

Ground vehicles traveling in an urban environment often change their speed rapidly, significantly affecting propulsive energy requirement. Figure 8 illustrates the speed profile of the United States Urban Dynamometer Drive Schedule (UDDS) and provides propulsive load curves for automobile parameters used in the model outlined in Appendix A on both UDDS and at the equivalent constant speed. While the propulsive load or surplus experienced during the UDDS can exceed 25 kW, the load at constant speed is about 1.5 kW. In the constant speed case, the vehicle incurs no energy losses from braking or within the kinetic energy recovery system and experiences overall lower aerodynamic drag. The model indicates that the propulsive energy requirement is 68% less at constant speed than on the UDDS.

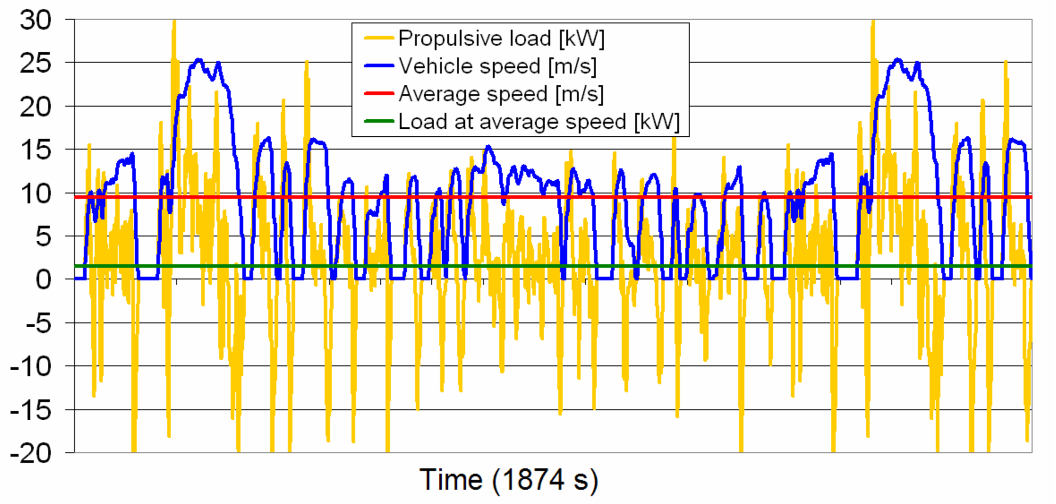

Figure 8: Vehicle motion and resistance on the UDDS and at constant speed

When non-propulsive vehicle loads are taken into account in a total vehicle system, speed profile still has a major impact on energy consumption. According the ADVISOR 2004 simulation software model of a modern hybrid vehicle, which includes drive train components and auxiliary loads, the total fuel consumption at constant speed is approximately 40% less than the equivalent time and distance on various urban driving cycles.

While no definitive estimates of speed profile improvement in a fully automated transportation system using conventional vehicles have been published, some studies indicate that the potentially improved response time, communication and coordination possible with automated vehicles could enable high throughput at relatively constant speeds [21,22]. Most current automated vehicle research includes work on automation of existing vehicle platforms to improve sensing, control, and fault detection [23]. An extremely low failure rate uncommon to other automated systems would be likely required for public acceptance of such a system. In addition, new transportation platforms may be enabled by, and possibly better suited to, automation.

Drag reduction

The final major component of transportation energy requirement is friction at the interface between the vehicle and the environment. This value is a combination of contact friction if the vehicle is traveling on a hard surface and, more importantly at high speed, viscous drag with the surrounding fluid. In systems utilizing magnets and conductors for suspension, drag losses can also include ohmic heating. Since friction is the dominant determinant of energy consumption at high speed, technical options that significantly reduce the viscous drag experienced by a moving vehicle could have a major impact on energy requirement and related greenhouse gas emissions.

Various transportation modes perform different functions and travel at a wide range of speeds, but all can be compared in terms of the transportation energy service they provide per unit friction drag. Figure 9 illustrates the cargo mass at maximum capacity per unit external friction force as a function of speed for examples of various transportation modes over a range of operating speeds. The dependent variable can also be expressed as cargo kilogram-meters per joule of energy dissipated to drag. As expected, the amount of cargo that can be carried per unit drag force decreases with increasing speed and is larger for freight transportation where cargo can be more closely packed. Since speed will be a premium in future transportation modes, the product of cargo mass per unit drag and speed, or the product of mass and distance traveled against friction per unit impulse, can represent a figure of merit for the effectiveness of a transportation mode. Most transportation modes currently operate at or slightly below their maximum effectiveness by this measure. For freight transportation, the cargo ship and freight rail have roughly equivalent effectiveness. Current commuter rail modes and the bicycle are roughly equivalent for passenger transport, but modern commercial aircraft are about 50% more effective. A magnetically levitated rail vehicle operating in an enclosure at 1% sea level air pressure could be an order of magnitude more effective than the aircraft, though it would likely require costly infrastructure.

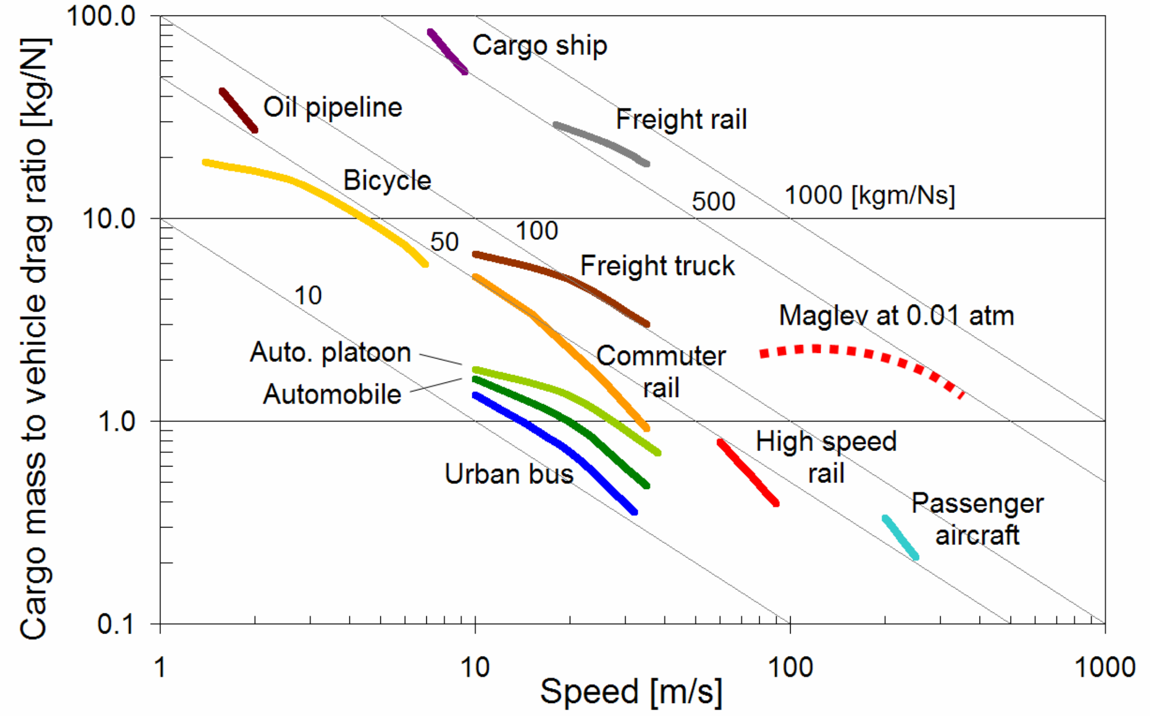

Figure 9: Cargo mass for various modes at a range of speeds [24-27]

Since the power required to overcome viscous drag is primarily a function of the drag coefficient, fluid density, and the cube of the velocity, little can be done at a set speed and air pressure except changing the shape. Modern high speed transportation vehicles as solitary units are fairly optimized in this respect and the field is largely understood, though system-scale changes to lower drag configurations may have a significant impact. For example, platoons of over four automobiles have an overall coefficient of drag less than one half of the value for isolated vehicles as the vehicle spacing approaches zero. Today’s vehicles in such a configuration would experience a drop in fuel consumption up to 30% [26].

Contact friction with the ground is often in the form of rolling friction and is rarely a dominant determinant of transportation energy requirement, especially at high speed and atmospheric pressure. Rolling friction decreases with the hardness and uniformity of the surface and rolling element and increases slightly with speed.

Magnetically levitated vehicles have a non-aerodynamic drag similar to vehicles with high quality steel wheels and rail at lower speeds, but this drag decreases at higher speeds and the lack of mechanical contact reduces damage to the vehicle and infrastructure [28,29]. The levitation system can be actively powered, often using superconducting coils to achieve high magnetic field densities, or passive, using only permanent magnets. In most designs, the magnetic drag decreases linearly with speed. This characteristic opens up a regime at low fluid density and very high speed in which these systems could be exceedingly effective if the energy requirement of maintaining the low density is small. Low density could be achieved through depressurizing and/or filling the enclosure with low density gases such as hydrogen or helium.

Part II: Carbon-free and carbon-neutral fuels

While decreasing transportation energy requirement proportionally reduces the associated greenhouse gas emissions, enabling the use of fuel cycles with low net greenhouse emissions could largely decouple emissions from the energy we do use. Many technical barriers hold back these alternative fuel cycles from large scale adoption including conversion efficiency, energy density, stability and cost.

There exist a wide array of proposed methods to collect energy from a resource and utilize it to move people and goods, many of which require multiple energy conversions and portable storage. Unlike large point source systems from which the capture and storage of CO_2 is considered a practical option for reducing net greenhouse gas emissions to the atmosphere, the mobile and distributed nature of transportation energy conversion makes diverting the flow of carbon to storage less attractive. For this reason, most proposed alternative energy carriers either do not contain carbon or use carbon collected from the atmosphere. Figure 10 illustrates some examples of low net carbon fuel cycle options. Since many of these fuel pathways are covered under other GCEP areas, the following sections focus on current research toward utilizing electricity in transportation and the production and use of non-fossil carbon-based fuels.

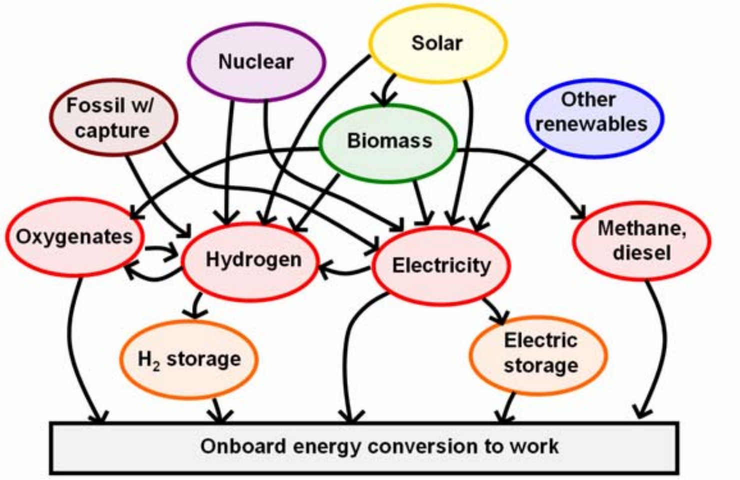

Figure 10: Various examples of the many potential low-carbon vehicle fuel cycle pathways

Electric energy utilization

Electricity is an important carbon-free energy carrier which has a large and growing infrastructure already in place. The possibility of storing electrical energy as the fuel for independent vehicles or electrically powering vehicles directly would be attractive if barriers such as low energy density, short lifetime, and high cost can be overcome.

Recent research has made significant advances toward overcoming these barriers, though much work remains before electricity is utilized in transportation on a large scale.

Portable electric energy storage can be accomplished by storing energy in a range of different forms including electrochemical and electrostatic energy storage devices. Electrochemical energy storage, or a battery, usually involves a reversible chemical reaction that can be driven to store energy when a voltage is applied and can subsequently release the stored energy to drive a load. Electrostatic energy storage includes devices where charge can be driven to bind to a surface and released when exposed to a load. Electrochemical energy storage has a much higher theoretical energy density, but current electrostatic devices have advantages in efficiency, cyclability and power capability.

Since the transported mass, in addition to the cargo, figures so prominently in vehicle energy consumption, any portable energy carrier must be relatively lightweight. Figure 11 summarizes the energy density and power density of various current and proposed portable electric energy storage devices in relationship to the properties of selected transportation fuels. The data for each battery chemistry represents an optimized cell for a given power density not including the cell packaging. Current batteries have energy densities over two orders of magnitude less than liquid fuels. Though the success of new battery chemistries under consideration could narrow this gap, it is likely that further advances will be required before vehicles with solely portable electric storage can achieve comparable levels of performance to current hydrocarbon fuelled vehicles.

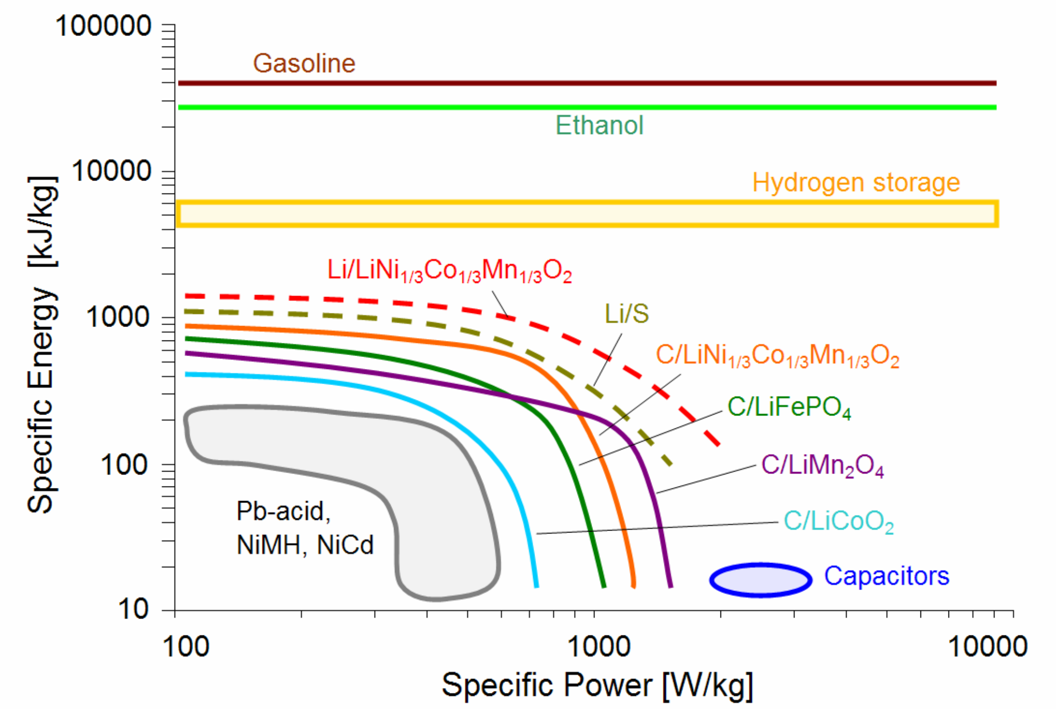

Figure 11: Specific energy and power of current and experimental portable energy storage [30-33]

Several strategies have been developed to minimize the mass of material relative to the stored energy and maintain reversibility over many cycles. One strategy involves transferring a lithium ion between two electrode structures through a conductive electrolyte. Each of the electrodes, the anode and cathode, are structured such that the lithium ion can be inserted and neutralized. The difference in insertion and neutralization chemical potential between the anode and cathode determine the voltage of the cell and the number of electrons that travel through the load determine the current. The voltage, current, and mass of these active components along with the electrolyte and mechanical structure of the cell all determine its specific energy. Specific power is related to the kinetics of these reactions and the ion transfer rate through the electrodes and electrolyte as well as the mass of the cell components.

The specific energy density of the electrodes is determined by the ion capacity, ion and material density, and voltage between each electrode. Current lithium ion batteries use a mixture of lithium and carbon at the anode and lithium cobalt oxide as the cathode with a wide array of lithium ion conducting materials for the electrolyte. A range of material combinations are currently under consideration to serve as higher energy density and more cost effective crystalline cathodes including manganese oxide, vanadium oxide, iron phosphate, and mixtures of cobalt, manganese oxide and nickel [34]. Manganese oxide batteries are less expensive, environmentally inert, and relatively stable, but are more limited in the fraction of lithium ions that can be stored in the cathode structure than other proposed chemistries due to their octahedral instead of layered geometry. Cobalt and nickel can be added to manganese oxide to stabilize the manganese oxide layers to prevent the octahedral structures from forming, leading to higher ion capacity. Iron phosphate cathodes are also relatively inexpensive and inert, but have a higher volumetric density than comparable chemistries [35]. Vanadium oxide batteries have exceptionally high lithium capacity, but store it at a lower voltage, leaving the overall energy density similar to other chemistries [36,37]. Each of these approaches has specific challenges with respect to stability, safety, and cost that have yet to be overcome [38-41].

Another electrochemical storage strategy, a redox couple between two light, active elements, provides a much higher theoretical energy density, but raises serious challenges for reversibility. One option that has been explored recently is the couple between lithium and sulfur [42,43]. With a theoretical energy density of nearly 10 MJ/kg active material, the energy storage density could approach that of many carbon-based fuels. However, current cell designs produce insoluable, non-conductive, low-order lithium sulfides that eventually destroy cell reversibility, especially at high rates of discharge. Electrolyte formulations and electrode geometry are currently being studied with a goal of allowing extended reversibility upon cycling and greater sulfur utilization.

Another approach to portable and reversible electric storage is high density capacitors. Though the storage efficiency, power density, and cyclability of capacitors are unmatched, the energy density is fundamentally small. In the case of carbon black capacitors, increasing the surface area beyond 1200 m^2/g does not increase the specific capacitance, as the space charge regions within the material begin to overlap. The maximum specific capacitance is about 100 F/g for porous carbon black double layer capacitors, which is approximately 300 kJ/kg at 2.5 volts [44]. This value is about an order of magnitude greater than the energy density of capacitors today. Capacitors may have an important role to play as a buffer in portable energy delivery systems that are unable to receive or deliver large bursts of power.

An alternative to portable high density energy storage is efficiently transmitting energy to the vehicle while in operation. One method of energy transfer from ground transportation infrastructure is through inductive coupling [45]. An alternating magnetic field could transfer energy to a relatively low energy density electric storage system onboard. Challenges include establishing an efficient inductive coupling over large air gaps and/or while a vehicle is in motion and developing electric storage devices capable of high charging rates.

Linear synchronous or induction motors also allow the use of electricity to propel a vehicle through the transmission of electromagnetic energy. At high speed, the energy transfer efficiency can exceed 90% [46]. Research into increased efficiency at a wide range of speeds and integration of the drive components with levitation in a combined system could help reduce the high cost of currently proposed systems.

Electrochemical synthesis and activation of carbon-based fuel

The high energy densities of carbon-based fuels make them an attractive energy carrier for mobile applications. However, in order to be part of a low greenhouse gas emissions energy future, carbon-based fuel cycles must close their carbon loops through methods including recycling carbon directly or only emitting carbon that was captured from the atmosphere originally. Both these methods require adding energy to upgrade CO_2 to an energy carrier and efficiently converting the energy carrier back to CO_2 and other products. Both the electrochemical reduction of CO_2 and fuel cells capable of directly converting carbon-based fuel to electricity offer the possibility of efficient and controlled methods to cycle carbon-based energy carriers without net CO_2 emissions to the atmosphere.

The electrochemical reduction of CO_2 to form hydrocarbons is poorly understood. Among the hydrocarbon syntheses that have been successfully demonstrated, current systems require costly catalysts, have low efficiency, or both [47-49]. The process requires the transfer of both electrons and protons, so a combination of inhibiting hydrogen formation while promoting the formation of the desired product is required. Copper based catalysts have shown the greatest propensity for converting CO_2 to hydrocarbons or alcohols, but current configurations have unacceptably low efficiency and selectivity. The large number of electron transfers that must take place to form a hydrocarbon suggests that multiple catalysis steps may be required for efficient and high throughput electrochemical reduction of CO_2 to fuels, requiring entirely new classes of catalysts.

Once a feasible method to synthesize carbon-based fuels from CO_2 has been developed, efficient methods to convert these fuels to useful energy will be required. While most fuels are converted into shaft work through combustion and the efficiency of these conversions is improving, electrochemical activation of carbon-based fuels offers an alternative route with the possibility of high efficiency and the direct production of versatile electricity. Fuel cells could be developed that use alkanes, alcohols, or other oxygenates directly as fuel. Just as CO_2 reduction to produce fuels has met considerable challenges, the electrochemical activation of these fuels may require entirely new approaches as well.

While conversion of single-carbon methanol has been successful, current direct ethanol fuel cells have poor performance and high cost [50,51]. With Sn promoted Pt catalyst configurations, complete oxidation of the ethanol is not achieved due to the difficulty in activating the C-C bond at low temperatures. Finding a catalyst configuration with lower over-potential and higher activity is a major barrier to efficient direct ethanol fuel cells.

Conclusions

Research leading to advances in both vehicle propulsive energy requirement reduction and low carbon fuel cycles will likely be required to provide sufficient options for transportation to join a low net greenhouse gas emissions energy system. The technical factors that determine transportation energy requirement for a given average speed and distance traveled were examined as well as several options for significantly reducing the net greenhouse gas emissions of energy carriers used for transportation. It was found that there is great potential for reducing greenhouse gas emissions associated with the transportation energy service and that fundamental research can play an important role in realizing this potential.

In the area of transportation energy requirement, vehicle mass is a dominant factor and has a large potential for reduction in passenger ground transport vehicles. Research that enables low-cost carbon fiber production and further development of strong, lightweight and energy absorbent polymer composites could replace many conventional vehicle materials. In addition, determining the feasibility and solving remaining technical barriers in contactless propulsion and levitation in low density fluid environments could enable unprecedented combinations of transportation speed and low energy requirement.

Many options exist for replacing fossil petroleum with carbon free or net carbon neutral energy carriers, though all require further research before adoption on a large scale. In addition to promising energy carriers not discussed in this report, electric energy storage and carbon-based fuels synthesized using low-carbon primary energy have the potential to significantly impact transportation greenhouse gas emissions if key barriers can be overcome. Electric energy storage density, cyclability, and economy must all increase to be adopted at scale. Improved, lower-cost conversion catalysts will be required for the success of low net emissions carbon-based fuels.

References

1. Schafer A, Victor D. The future mobility of the world population. Transportation Research Part A 2000;34:171-205.

2. Proost S, van Regemorter D. Are there cost-efficient CO2 reduction possibilities in the transport sector? - Combining two modelling approaches. Int. J. of Vehicle Design 2001;26(2/3):116-130.

3. World Energy Outlook 2005. IEA, Paris, 2005.

4. IEA Key world energy statistics 2005. IEA, Paris. See also: http://www.iea.org/dbtw-wpd/Textbase/nppdf/free/2005/key2005.pdf

5. ORNL Transportation Energy Data Book: Edition 24, 2005. See also: http://www-cta.ornl.gov/data/Index.html

6. Automotive Lightweighting Materials, EERE FY 2004 Progress Report, p.162, 2005.

7. Boeing 787 Dreamliner Program Fact Sheet. The Boeing Company, Chicago, 2005. See also: http://www.boeing.com/commercial/7e7/programfacts.html.

8. Farley GL. Energy Absorption of Composite Materials. Journal of Composite Materials 1983;17:267-279.

9. The research requirements of the transport sectors to facilitate an increased usage of composite materials, Part 1: The composite material research requirements of the aerospace industry. Compositn 2004, Chesterfield UK. See also: http://www.netcomposites.com/images/CompositeN_Aerospace.pdf.

10. MatWeb, Material Property Data, 2005. Automation Creations, Inc of Blacksburg, Virginia. See also: http://www.matweb.com.

12. Miyagawa H, Mirsa M, Mohanty AK. Mechanical properties of nanotubes and their polymer nanocomposites. Journal of Nanoscience and Nanotechnology 2005;5:1593-1615.

13. Jayamathy M, Kailas SV, Kumar K, Seshan S, Srivatsan TS. The compressive deformation and impact response of a magnesium alloy: Influence of reinforcement. Materials Science & Engineering A 2005;393(1-2):27-35.

14. Nam HW. Aggag GA, Takahashi K, Han KS. Dynamic behavior of metal-matrix composites under low-velocity impact. Composites Science and Technology 2000;60(6):817-823.

15. Rawal S. Metal-Matrix Composites for Space Applications. JOM 2001;5(4):14-17.

16. Dhoble A, Kulshreshtha B, Ramaswami S, Zumbrunnen DA. Mechanical properties of PP-LDPE blends with novel morphologies produced with a continuous chaotic advection blender. Polymer 2005;46(7):2244-2256.

17. Thostenson ET, Li C, Chou TW. Nanocomposites in context. Composites Science and Technology 2005;65:491-516.

18. Minus ML, Kumar S. The processing, properties, and structure of carbon fibers. JOM 2005;57(2):52-8.

19. Zhu J, Peng H, Rodriguez-Macias F, Margrave JL, Khabashesku VN, Imam AM, Lozano K, Barrera EV. Reinforcing epoxy polymer composites through covalent integration of functionalized nanotubes. Advanced Functional Materials 2004;14(7):643-648.

20. Chang DJ, Morlok EK. Vehicle speed profiles to minimize work and fuel consumption. Journal of Transportation Engineering 2005;131(3):173-182.

21. Parent M. From drivers assistance to full automation for improved efficiency and better safety. IEEE 59th Vehicular Technology Conference 2004;5:2931-4.

22. Stephan CH, Miller JM, Craig DL. A program for individual sustainable mobility. International Journal of Vehicle Autonomous Systems 2004;2(3-4):255-77.

23. Shladover SE. Automated vehicles for highway operations (automated highway systems). Journal of Systems and Control Engineering 2005;219:53-75.

24. Rochard BP, Schmid F. Review of methods to measure and calculate train resistances. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 2000;214(4):185-199.

25. Suppes GJ. Perspectives on maglev transit and introduction of personal rapid transit maglev. Transportation research record 1995;1496:103-111.

26. Zabat M, Stabile N, Frascaroli S, Browand F. The aerodynamic performance of platoons: final report. California PATH, Institute of transportation studies, UC Berkeley, Report No. UCB-ITS-PRR-95-35, October 1995.

27. Schetz JA. Aerodynamics of high-speed trains. Annu. Rev. Fluid Mech. 2001; 33:371–414.

28. Gurol S, Baldi B. Overview of the general atomics urban Maglev technology development program. ASME/IEEE Joint Rail Conference 2004, Baltimore, MD, USA; 187-91.

29. D'Ovidio G, Lanzara G, Crisi F, Navarra A, Villani M. Light rail Maglev with superconductor materials: System design. Advances in Transport 2003;14:657-665.

30. Meeting the Energy Needs of Future Warriors, National Research Council of the National Academies 2004. See also: http://www.nap.edu/books/0309092612/html.

31. Akridge JR, Mikhaylik YV, White N. Li/S fundamental chemistry and application to high-performance rechargable batteries. Solid State Ionics 2004;175:243-245.

32. Choi YS, Kim S, Choi SS, Han SJ, Kim JD, Jeon SE, Jung BH. Effect of cathode component on the energy density of lithium-sulfur battery. Electrochimica Acta 2004;50:833-835.

33. Andrew Burke, Energy Storage in Advanced Vehicle Systems. Global Climate and Energy Project Advanced Transportation Workshop, Stanford University, October 12, 2005.

34. Whittingham, MS. Lithium batteries and cathode materials. Chemical Reviews 2004;104(10):4271-4301.

35. Yang SF, Song YN, Ngala K, Zavalij PY, Whittingham, MS. Performance of $LiFePO_4$ as lithium battery cathode and comparison with manganese and vanadium oxides. Journal of Power Sources 2003;119-121:239-246.

36. Chen CG, Liu YP, Li L. Development of vanadium oxide in lithium ion batteries. Journal of Inorganic Materials 2004;19(6):1225-1230.

37. Winny D, Sakamoto JS, Bruce D. Electrochemical properties of vanadium oxide aerogels. Science and Technology of Advanced Materials 2003;4(1):3-11.

38. Vetter J, Novak P, Wagner MR, Veit C, Moller KC, Besenhard JO, Winter M, Wohlfahrt-Mehrens M, Vogler C, Hammouche A. Ageing mechanisms in lithium-ion batteries. Journal of Power Sources 2005;147(1-2):269-281.

39. Wohlfahrt-Mehrens M, Vogler C, Garche J. Aging mechanisms of lithium cathode materials. Journal of Power Sources 2004;127(1-2):58-64.

40. Akridge JR, Mikhaylik YV, White N. Li/S fundamental chemistry and application to high-performance rechargeable batteries. Solid state ionics 2004;175:243-245.

41. Kanevskii LS, Dubasova VS. Degradation of lithium-ion batteries and how to fight it: a review. Russian Journal of Electrochemistry 2005;41(1):3-19.

42. Shim J, Striebel KA, Cairns EJ. The lithium/sulfur rechargeable cell. Journal of the Electrochemical Society 2002;149(10):A1321-5.

43. Zhu X, Wen Z, Gu Z, Lin Z. Electrochemical characterization and performance improvement of lithium/sulfur polymer batteries. Journal of Power Sources 2005;139:269-273.

44. Barbieri O, Hahn M, Herzog A, Kotz R. Capacitance limits of high surface area activated carbons for double layer capacitors. Carbon 2005;43:1303-1310.

45. Wang CS, Covic GA, Stielau OH. Power transfer capability and bifurcation phenomena of loosely coupled inductive power transfer systems. IEE Transactions on Industrial Electronics 2004;51(1):148-157.

46. Fujii N, Hoshi T, Tanabe Y. Methods for improving efficiency of linear induction motor for urban transit. JSME International Journal, Series C (Mechanical Systems, Machine Elements and Manufacturing) 2004;47(2):512-517.

47. Scibioh MA, Viswanathan B. Electrochemical reduction of carbon dioxide: a status report. Proc. Indian National Science Academy 2004;70(3):407-462.

48. Ogura K. Electrochemical and Selective Conversion of CO2 to Ethylene. Electrochemistry 2003;71(8):676-680.

49. Arakawa H, Aresta M, Armor JN, Barteau MA, Beckman EJ, Bell AT, Bercaw JE, Cruetz C, Dinjus E, Dixon DA, Domen K, DuBois DL, Eckert J, Fujita E, Gibson DH, Goddard WA, Goodman DW, Keller J, Kubas GJ, Kung HH, Lyons JE, Manzer LE, Marks TJ, Morokuma K, Nicholas KM, Periana R, Que L, Rostrup-Nielson J, Sachtler WMH, Schmidt LD, Sen A, Somorjai GA, Stair PC, Stults BR, Tumas W. Catalysis Research of Relevance to Carbon Management: Progress, Challenges, and Opportunities, Chemical Review 2001;101:953-996.

50. Lamy C, Rousseau S, Belgsir EM, Coutanceau C, Leger JM. Recent progress in the direct ethanol fuel cell: development of new platinum-tin electrocatalysts. Electrochimica Acta 2004;49:3901-3908.

51. Song SQ, Zhou WJ, Jiang LH, Sun GQ, Xin Q, Leontidis V, Kontou S, Tsiakaras P. Direct ethanol PEM fuel cells: the case of platinum based anodes. International Journal of Hydrogen Energy 2005;30:995-1001.

52. Post RF, Ryutov DD. The Inductrack: a simpler approach to magnetic levitation. IEEE Transactions on Applied Superconductivity 2000;10(1):901-904.

Appendix A

The simplified models used in the introduction and Part I of this assessment are primarily intended to illustrate facets of transportation energy requirement and do not purport to be definitive analyses or comparisons of transportation mode performance. However, reasonable assumptions were made in an attempt to produce results that are fair and accurate enough for the purpose of illustration. For the interested reader, the assumptions underlying these models are outlined below.

The vehicle model developed determines propulsive vehicle loads and energy dissipation from simple relationships which require data for various vehicle characteristics and vehicle speed. Assumed characteristics of the individual vehicles modeled are provided in Table 2. Unless otherwise noted, the aerodynamic drag and contact friction were calculated as follows:

$$D_{aero} = 0.5 \rho_{air} C_d \, A_{front} \mathrm{V}^3$$

$$D_{rolling} = \mu_{rolling} \, m \, g$$

where C_d is the drag coefficient, A_{front} is the frontal area, V is the speed, and $\mu_{rolling}$ is the coefficient of rolling friction. The kinetic energy recovery systems were modeled on an "as needed" basis. If energy is required for vehicle propulsion, any energy stored in the battery is used first. The kinetic energy regeneration factor for all vehicles in figure 4 was assumed to be 0.7 and the generator/battery efficiency was 0.85.

Table 2: Vehicle characteristics

Vehicle	Gr. Mass [kg]	Cargo [kg]	C_d	Area [m^2]	$\mu_{rolling}$	Max. regen [kW]
Bicycle	75	67	0.9	0.3	0.0044	n/a
Auto	1400	252	0.29	1.88	0.009	14
Auto platoon	1400	242	0.145	1.88	0.009	14
Comm. Rail	27000	4590	0.86	7	0.002	1000
Urban bus	11400	1938	0.9	8	0.009	100
HS rail	440000	35200	*	*	*	1000
Maglev rail	440000	35200	*	*	*	1000
Pass aircraft	204500	20450	0.024	362	n/a	n/a
Freight truck	36280	23950	0.65	10	0.009	n/a
Freight rail	2.2E6	1.58E6	6.5	8.8	0.002	n/a
Cargo ship	215E6	187E6	n/a	n/a	n/a	n/a

Some vehicle models have special aspects that require unique assumptions. The models for the high speed rail and maglev modes were based on a 300 m train similar to the

Shinkansen 300, using the resistance formula developed by SNCF for the TGV network [24]. For the maglev, the rolling drag term was replaced by the theoretical magnetic drag of the passive Inductrack II system [52]. In addition, a tunnel aerodynamic drag factor of 2 is added for the low pressure maglev mode. The pumping energy requirement to maintain the low pressure environment was assumed to be small. The pipeline was assumed to have a diameter of 1.22 m and transfers fluid with density of 887 kg/m^3 and a viscosity of 0.036 Ns/m^2 against a smooth steel surface. The cargo ship uses a basic ship resistance formula using the displacement and hull geometry of the SeaRiver Mediterranean oil tanker.