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**Title:****Renewable Energy Utilization Advantages of Maglev-Based Personal Rapid Transit****Submission Date: March 14, 2010****TRB reference: 10-0815****Text word count: 5,998****Figure Count: 3****Table Count: 1****Total Word Count: 6,998****AUTHORS:****Corresponding Author****Robert Baertsch****NASA Ames Research Center****Sustainable Transportation Research****NASA Ames Research Center****Mail stop 19-100****Moffett Field, California 94035****United States****Phone: 831-239-2531****Email: robert.baertsch@gmail.com****Fax: 650-838-9313****Jared Dunnmon****Duke University****P.O. Box 93536****Durham, North Carolina 27708****United States****Phone: 5134778441****Email: jad44@duke.edu**

## **ABSTRACT**

This paper examines the advantages that Maglev Personal Rapid Transit (MPRT) exhibits in the utilization of renewable energy from usage, distribution and generation. The paper also looks at different types of PRT and how they impact the load on the electrical grid. Recent advances in power electronics and maglev technology allow for the design of a novel MPRT system characterized not only by exceptionally low power requirements, but also by a unique capacity to incorporate energy distribution and storage infrastructure into the greater transportation architecture. A hypothetical hybrid MPRT design incorporating energy storage and transmission capabilities is presented. In addition, thorough carbon dioxide and cost analyses are undertaken in order to more fully understand the spectrum of benefits of an MPRT solution in comparison to Conventional Vehicle (CV) and Plug-in Hybrid Electric Vehicle (PHEV) approaches. We conclude that an MPRT system not only offers significant advantages over other technologies in efficiently utilizing renewable energy, but also it represents the unique potential to address urgent energy challenges by incorporating power transmission, storage and generation infrastructure.

## BACKGROUND

The first automated vehicle system using Personal Rapid Transit (PRT) architecture was built in the 1970s in Morgantown, West Virginia. PRT architecture is a guideway topology that provides on-demand service in a manner very similar to the automobile. PRT architecture enables the discrete movement of a personal “car-like” vehicle (“a packet”) by switching it through a network, akin to a physical internet. Automation dramatically reduces congestion and improves safety as humans are replaced in the active control loop. A passenger never waits for a personal vehicle at a station and the only stop made is at the selected destination in the network.

Currently, a number of companies around the world are developing second-generation PRT systems. Like first-generation systems, they use wheels and travel at top speeds of 25-30 mph but are distinguished by their use of advanced composite materials and modern automation systems. Maglev-based PRT (MPRT), what some have termed a “third-generation” PRT system, is radically different from all other PRT systems in that it uses passive magnetic levitation (“maglev”) for locomotion, allowing both for high-speed capability and extremely low maintenance. In order to encourage a widespread switch from gasoline-powered cars to PRT, it is imperative that the system move at highway speeds. It is very difficult to achieve this goal with wheeled PRT systems due to their small wheel size and associated frictional losses. The transformational power of MPRT technology results from its unique combination of Personal Rapid Transit (PRT) architecture with ultra energy-efficient, low-cost, passive maglev-based linear synchronous motor (LSM) powertrain.

One of the greatest advantages of an MPRT system is its ability to adapt to any given transportation environment. MPRT vehicles can, for instance, run at speeds as low as 20-30 mph (32-48 kph) in airports and business districts while moving at speeds of up to 150 mph (241 kph) between cities. This makes MPRT time competitive with air travel at distances of up to 500 miles (805 km) by avoiding time-consuming airport security and runway delays (1). A single guideway using 3-passenger vehicles at ½-second headways, moreover, has the potential to carry 21,600 passengers per hour, more than a four-lane freeway. Widespread implementation with this spectrum of benefits could represent a transformational advance in the transportation paradigm when compared to conventional automobile and public transit capabilities. In essence, MPRT takes Intelligent Transportation System-Automated Highway System scenarios involving fully automated automobiles to their logical conclusion by autonomously providing point-to-point transportation for both passengers and freight. By avoid mixing legacy vehicles with automated transport, MPRT overcomes hurdles that has limited adoption of automated highways.

MPRT, then, is essentially an electric-powered transportation system that borrows from the architecture of the automobile in the sense that private, high-speed point-to-point transport is possible utilizing a traffic plan similar to that of the freeway. With the twin problems of climate change and peak oil looming, it is imperative to speed the transition to renewably powered ground transportation. Plug-in hybrids (PHEVs) and electric-powered mass transit might achieve this goal, but each has problems that have slowed implementation. Battery technology presents a significant hurdle for mass

production of plug-in hybrids in both technological and economic terms. According to the USABC, for instance, current state-of-the-art PHEV-type batteries cost 4-5x more than required for commercialization (2). While mass transit is limited by human factors and high cost, MPRT offers the promise of renewable-powered transport without the delays and fixed schedule of mass transit. This frees the passenger from traffic congestion and down-time behind the wheel of an automobile. Given historical growth in Vehicle Miles Traveled ("VMT") of 1.7% from 1.1 trillion in 1970 to over 3 trillion in 2008 (3), the United States is facing a need to constantly widen highways. While PRT was first developed in the 1970s, it never achieved widespread adoption due to an abundance of inexpensive petroleum and a distinct lack of the significant computational power required to build large networks. Awareness of impending peak-oil and climate-change challenges, combined with recent advances in magnetic levitation technology, advanced computer networking software, renewable power systems and energy storage methodology positions MPRT as an ideal candidate for consideration as the next generation of renewable transit.

## **MPRT INFRASTRUCTURE OVERVIEW**

### **Physical Structure**

Maglev-LSM technology provides high-speed propulsion, making scalable local, regional and national networks possible. Energy efficiency is optimized using lightweight, aerodynamic vehicles capable of handling payloads of up to 1200 lbs (544 kg) or up to four passengers. Lighter two-person vehicles with payloads of up to 500 lbs (227 kg) could also be utilized. Lightweight vehicles allow for slim guideway structures that can be suspended on steel poles similar in size to those used to support traffic lights. These overhead guideways could be composed of recycled steel and mounted on poles that are spaced between 30 and 100 feet (9-30 m) apart, depending on local conditions. Given their extremely low footprint, these poles could be mounted in such unobtrusive spaces as above sidewalks, in street medians, or along the edges of highways. In cases where trees hang over the road, the guideway can be suspended over a lane of traffic from an arch that spans the street. Switching will allow vehicles to leave the main guideway at speed and decelerate into elevated stations that are below the level of the main guideway. Stairs and ADA-compliant elevators allow for access to these stations, which can also be easily designed for bicycle accessibility. Special vehicles for carrying freight will be sized to fit a standard pallet. Portals will be positioned every ¼ to ½ mile along the guideway to maximize access to the system. The only land required will be areas for elevators and stairs to access portals.

### **Power Electronics**

Testing completed on large rotary wheel demonstrates that the LSM system characteristic of recent MPRT concepts is 93% efficient in translating electrical into kinetic energy, leading to a round trip regenerative braking efficiency of 86% (John Cole, Unimodal Systems, personal communication). When the vehicles decelerate, their kinetic energy transfers back to the DC power bus and into the system storage or the power grid

with less than 10% power loss as opposed to being stored in relatively loss-prone chemical batteries. Just like a speed boat rides higher on a wave with increasing speed, passive-maglev device does not require energy to induce levitation. The forward motion of the LSM induces a magnetic wave in the guideway levitation coils which is opposed by the magnets in the vehicle. While in motion, the vehicles are rigidly and precisely fixed in the vertical dimension by powerful repulsive magnetic forces creating an inherently stable system without active control. This results in an inexpensive and highly reliable system.

### **Passive EDS, Superconducting EDS and EMS Magnetic Levitation**

Maglev technology has changed significantly in the last 20 years. Traditional EMS systems use electromagnets for levitation and a control system that must vary the magnetic field, resulting in an inherently unstable system. Superconducting electrodynamic suspension (EDS) systems (1) are inherently stable, but have a huge capital and operating cost needed to maintain liquid nitrogen to cool the magnets. These features, combined with power requirements needed for levitation, make these systems very expensive. More recently, systems based on passive (EDS) magnetic levitation, requiring no power for levitation, have been proposed that can be manufactured at low cost in high volume (4). This arrangement allows for reduced guideway structural requirements and for the safe use of vehicles hanging from underneath the guideway, which swing out in response to turning forces. Utilizing this type of vehicle provides greatly improved passenger comfort, higher cornering speeds, higher switching speeds, and reduced torsion on the guideway support structure. Unlike conventional maglev designs that use superconducting magnets requiring complex backup power systems, vehicles using passive maglev respond to a catastrophic power loss by continuing to levitate using the momentum of the vehicle until gliding gently to a low speed before settling onto the track surface. The absence of moving parts in both guideways and vehicles along with non-contact, friction-free vehicle motion ensures high reliability and extremely low maintenance requirements. Tightly integrated LSM propulsion provides high force application and power transmission capabilities that enable rapid acceleration and steep-grade climbing. Regenerative braking capability similar to that used in hybrid automotive vehicles improves overall system efficiency. The integration of passive maglev and LSMs enables the design of modular, mass-produced components, resulting in low-cost systems that are crucial for building large networks without tax subsidies.

Another advantage of putting the motor in the guideway is that it allows for single vehicle continuous power requirements as low as 2-3kW during normal operation (5), (6), (7), (8). Since MPRT is non-stop and power from regenerative braking does not necessarily need to be stored in a battery, the average power requirements are very close to the power needed for normal operating speed. At an average speed of 50 mph, this power requirement translates into an average energy consumption of around 100 Wh per mile (62 Wh per kilometer) (5). In comparison with PHEVs, which range from 200-500 Wh per mile (124-311 Wh per kilometer), MPRT could offer significant energy consumption advantages (6), (7). In addition to high-efficiency motors, the power electronics that connect the system to the grid can use active power control to maintain

system efficiency at power factor one. This decreases reactive loads on the grid and avoids extra utility charges from wasted power that is typical in motor applications. Moreover, in contrast with wheeled systems in which rolling resistance increases with speed, the magnetic drag resultant from levitation actually decreases with increased speed, allowing for higher average system speed while continuing to meet energy efficiency goals.

## **MPRT INTERACTION WITH THE POWER DISTRIBUTION GRID**

One of the distinct disadvantages of current transportation infrastructure is its disconnection from power transmission infrastructure. This state of affairs makes large-scale low-emission transit propositions based on non-modular electricity utilization extremely difficult to implement. The establishment of the electric segment of the San Francisco municipal bus fleet, for instance, required intricately networked hanging power lines well beyond the basic requirements of the power grid to be installed over the middle of every street in the city used by these electric buses. While this might be a workable solution in dense urban areas, such constructs would be neither welcome nor viable over regional highways or in suburban areas, not to mention their significant expense. In addition, with the United States Department of Energy currently allotting \$4.5 billion to the Office of Electricity Delivery and Energy Reliability in order to upgrade the current U.S. power grid, the issue of how to best construct the next generation of energy distribution infrastructure has become salient (9). Of particular interest is how to design such a grid system that can handle the centralized generation paradigm of the present while retaining the ability to adapt to future distributed generation capacity.

While many do not associate transit challenges with the transmission grid problem, MPRT has the unique ability to help solve both infrastructural dilemmas at once. MPRT infrastructure requires power electronics in order to deliver energy to the individual transportation units. This requirement, while sometimes assumed a disadvantage of MPRT, can actually be a significant benefit of the technology because it enables it to serve as an effective power distribution system. Further, it transfers the weight of the motor, gear box and fuel storage out of the vehicle and into the guideway, thus increasing system efficiency. In addition, it strengthens the electric power grid by providing an alternative pathway for power transmission and distribution. By adding a 12kV power line to the guideway, at a cost of 1 million dollars per mile (\$620,000 per kilometer this could allow for such an integrated MPRT system to become reality. In light of the fact that the current estimated cost of installing new power infrastructure is 2-4 million dollars per mile, the implementation of an MPRT-based distribution system appears viable from an economic standpoint (10).

## **Integrating Transportation and Power Distribution**

Current centralized generation systems require large transformers and dedicated high voltage power lines to shunt energy over long distances, which results in significant resistive heat loss. In fact, distribution losses in the U.S. were estimated at as much as 7.2% of the total energy generated in 1995 (11). Particularly with energy prices projected

to increase in the coming decades, avoid losses in transmission is much cheaper than adding new grid capacity. In order to address this issue and to reduce the amount of needed distribution capacity associated with transitioning from liquid fuel to electric transport, MPRT allows distributed energy sources to be placed along the guideway as well as incorporating transmission capacity within the guideway, thereby minimizing transmission distance and resistive heat loss. Distributed renewable energy sources could either be directly utilized to power the MPRT system, stored in utility-scale storage mechanisms to power the system during off-peak generation times, or distributed to nearby communities. Moreover, given the recent national emphasis on regional planning and transit-oriented development, routing MPRT near generation sites would potentially result in indirect generation-oriented development, which would further decrease transmission loss. Combining long haul transport through remote windy areas would be useful for harnessing stranded wind generation capacity.

In addition to its distribution capacity, one of the more important advantages of MPRT systems is the ability to incorporate renewable-energy generation into its design. Individual vehicles could have average power requirements as low as 3 kW at 30 mph and 6 kW at 50 mph, which, at projected MPRT speeds, implies energy requirements of 100-200 Wh per mile (62-124 Wh per kilometer) as opposed to the 200-500 Wh per mile (124-311 Wh per kilometer) characteristic of electric vehicles and EV PRT systems (12). Assuming ridership of 100,000 vehicles per day we calculated an energy requirement of 10-20,000 kWh per mile of guideway per day. Using current PV technology, covering the topside of a PRT track with photovoltaic panels of 8-foot (2.4 m) width would be sufficient to provide enough electricity to power the system at capacity, assuming an average operational speed of around 50 mph (80 kph) (13). Even with this added cost, a bi-directional MPRT system would still cost only \$15-18 million per mile (\$9-11 million per kilometer), which compares favorably to other forms of transportation infrastructure. However, due to the phase difference between solar energy and traffic patterns, either storage or supplemental power must be provided (See Figure 1). Solar technology, however, is not the only way this system could make use of renewable generation technologies. Solid oxide fuel cells powered by natural gas provide a lower GHG footprint than traditional sources due to their high efficiency (14). By positioning fuel cells at every mile along the guideway, one could design an MPRT system to have a continuous source of power and to provide excess power back to the grid during periods of low ridership. Assuming a lower average daily ridership of 30,000 passengers, a single 100 kW fuel cell per mile (1.6 kilometers) combined with a 2-foot (0.6 m) wide PV panel on the top surface of the guideway could also provide 100% of the power needs for a MPRT system running at an average speed of 50 mph (80 kph). Running these fuel cells off of renewable synthetic biogas would increase the system's utilization of renewable generation methods. Moreover, including such fuel cells would allow for on-demand generation that might more effectively handle large peak loads, particularly during off-peak solar generation hours, than a system supplied solely by solar power.

## **MPRT Energy Storage Integration**

One of the more salient questions this analysis raises is how to manage power requirements during peak loads. PHEV systems mitigate this problem by charging at night, but at a huge cost of requiring 100% of energy used to be stored in a battery. MPRT has two advantages: (1) energy storage is only needed for peak times, and (2) it is cheaper and more efficient to store energy using stationary technologies. An example using a combined PV, fuel cell application demonstrates that only 30% of the required energy needs to be stored is shown (Figure 2).

For urban transit segments, it would be viable for distributed-generation equipped MPRT infrastructure to release power directly into the urban grid, thereby providing significant generation capacity for a city or neighborhood. In more isolated suburban and rural areas where off-peak electricity consumption can vary widely, storage systems could be utilized to store excess energy generated during these off-peak consumption hours that could be used to power the MPRT system at off-peak generation periods. There are a number of viable large scale battery technologies available to perform this energy storage function, a topic on which the Sandia National Laboratories has composed an extensive report (15). Using current technologies, sodium-sulfur, pumped hydro and vanadium redox chemistries would make the most sense in a renewable utility grid support capacity. Calculations indicate that running the system at an average capacity of 30,000 riders per day would require stationary energy storage of 1,000-2,000 kWh per mile at a cost of around \$1-2 million per mile (\$620,000-1,240,000 per kilometer). For our example of a network for California, this works out to about \$500 per user. PHEVs will require at least \$5,000 per car assuming the problems with batteries can be solved. Overall, the use of utility-scale power storage, as opposed to the mobile power storage required by PHEVs, could at present result in savings of up to \$700/kWh. Kammen estimates the current upper bound on PHEV energy storage price as \$1300/kWh while Sandia conservatively reports an average cost of \$600/kWh for current large scale vanadium redox applications, a cost that is expected to see continuing decreases as the technology is refined (15), (16). If future transportation infrastructure is to have the capacity to economically perform a dual function as part of the power transmission grid, energy storage, an integral part of the new renewable smartgrid concept, must be purchased at the most favorable cost per unit energy capacity. Clearly, the numbers above indicate that integrating utility-scale power storage capacity into the transportation architecture would be a much more cost-effective option than attempting to accomplish power storage through modular EV batteries, as some have suggested. Moreover, the fact that MPRT utility-scale power storage could interface directly with the general area power grid and store excess energy could dramatically increase an area's flexibility in terms of how it chooses to generate and use energy.

## **GREENHOUSE GAS AND ECONOMIC COST ANALYSES**

## Carbon Dioxide Emissions Analysis

This section proposes a hypothetical case study to address the local and regional GHG reductions associated with displacing 50% of California's traditional vehicle miles traveled (VMT) on state highways with MPRT.

Personal vehicle travel on California's state highways is responsible for 176 billion VMT (283 billion VKT) on an annual basis (17). Available fuel usage data for cargo trucks indicates that annually this particular class of vehicle uses 1.4 billion gallons of diesel fuel. Assuming an average fuel efficiency of 6 miles per gallon (9.6 kilometers per gallon), this implies that trucks are responsible for 8.4 billion of the 176 billion total state highway VMT (18). Moreover, this would suggest that the remainder of those VMT, on the order of 167.6 billion, comes from passenger cars. Equally distributed displacement of half of total state highway VMT would therefore result in the displacement of 0.7 billion gallons of diesel fuel and, assuming a 22 miles per gallon (35.4 kilometers per gallon) average fuel economy for passenger cars, 3.8 billion gallons of gasoline (19). These numbers translate into 36.9 million tons of CO<sub>2</sub> emitted from personal vehicles on state highways in addition to 7.75 million tons from cargo truck traffic for a total of 44.65 million tons of carbon dioxide (20). Thus, the emissions from 50% of VMT on California's state highways represents a full 22.2% of California's 201.29 million tons of annual CO<sub>2</sub> emissions from ground transportation (21).

Given such VMT data, comparing the CO<sub>2</sub> emissions benefits of various transportation scenarios becomes a relatively simple process once emissions per VMT can be calculated for each scenario. For conventional vehicles (CVs), the results will be no different from those presented directly above. Several studies have been performed to determine what fraction of petroleum usage is displaced by various PHEV systems. A recent PHEV cost-benefit analysis performed at the National Renewable Energy Laboratory concluded that a PHEV60 system (a PHEV system with a 60-mile all-electric range), the largest considered, could in fact displace a full 60% of petroleum usage (22). Utilizing this proportion, one can conclude that the total amount of CO<sub>2</sub> emitted by passenger cars on California state highways by a PHEV60 displacement of 50% VMT would be on the order of 14.74 million tons of CO<sub>2</sub>. Because no relevant numbers are available for trucks, it is reasonable (and also necessary) to assume that at least 50% of truck traffic contains objects that could be fitted into smaller containers. Dividing the average capacity of a cargo truck by the maximum payload of a generic MPRT pod results in a VMT adjustment factor of approximately 20. Multiplying freight VMT by this factor will give the equivalent freight-based MPRT VMT necessary to displace the appropriate fraction of cargo truck VMT. Using the numbers available for PHEV-powered cargo trucks (a concept that is, moreover, currently of tenuous practicality), we make the assumption that technologically a cargo truck-sized PHEV60 system could ultimately achieve the same utility factor (i.e. percentage of fuel displaced by a PHEV) in displacing 60% of the relevant diesel fuel usage (22). Iterating this assumption through the CO<sub>2</sub> calculations results in a cargo truck CO<sub>2</sub> contribution of 3.10 million tons, meaning that in total the 44.65 million tons of CO<sub>2</sub> resultant from performance of these VMT by conventional means would be displaced by 17.84 million

tons with a PHEV solution. This 26.81 million ton reduction represents a 9.9% decrease in the state's overall CO<sub>2</sub> emissions from ground transportation and displaces 60% of possible emissions per VMT under consideration.

First we perform a similar analysis using an MPRT solution using the current California power generation mix, followed by a system powered by renewables. Specifications from a recent MPRT prototype indicate that the only energy the system utilizes is approximately 100 Wh of electricity per VMT (62 Wh per VKT) at an average speed of 50 mph (80 kph). Given that the California energy generation mix averages out to emitting 108 g CO<sub>2</sub>/kWh, this particular MPRT system would then emit net 11.9 tons CO<sub>2</sub> per million VMT. Dealing with the displaced freight VMT in an MPRT setting becomes more difficult because, while the same fuel is used, it requires several pods to transport the same amount of freight that a single cargo truck can transport. Assuming a pod with a given maximum internal volume and payload, calculating the total CO<sub>2</sub> emissions from freight transport by MPRT requires an adjustment factor directly proportional to the number of pods required to transport the same capacity as a generic cargo truck. Because only calculated above, then, it becomes apparent that the personal transit VMT result in 0.998 million tons CO<sub>2</sub> while the freight VMT result in 1 million tons CO<sub>2</sub> using an MPRT solution, thereby giving a very low net emission figure of 1.998 million tons CO<sub>2</sub>. Extending these results illustrates that the 42.72 million ton reduction from a CV solution represents a full 21.2% of California state emissions from ground transportation and a displacement of an astounding 95.5% of possible emissions per VMT replaced by MPRT trips. Clearly, then, while the best possible PHEV solution does offer significant CO<sub>2</sub> emissions reductions, an MPRT system is nonetheless more than 30% more effective. It is true that these figures use generally cleaner California power; but while the absolute emissions numbers may be depressed because of this fact, the magnitude of the relative efficacy of the two solutions presented above will certainly not be altered substantially.

### **Economic Analysis**

A final point that merits consideration is how the lifecycle monetary cost of an MPRT VMT diversion solution compares with that of an analogous CV or PHEV solution. The Santa Cruz County Regional Transportation Commission (SCCRTC) provides a thorough assessment of average cost per VMT for current CVs, including such costs as finance charges, depreciation, fuel, maintenance, parking, tolls, travel time with average delays, accidents, road maintenance, roadway land value and other relevant metrics (23). The only mathematical difference from the included sections of the SCCRTC analysis was that an average gasoline price of \$3.50 rather than \$3.00 was assumed. Computations resulted in an average per VMT cost of \$1.24 per VMT (\$0.77 per VKT) over the lifetime of a conventional vehicle. While performing a similar analysis for PHEVs can be difficult due to a lack of knowledge about their long-term performance and costs, an evidence-based modification of the SCCRTC analysis was performed in order to inform a high-level estimate of total lifetime costs per VMT for PHEV60 vehicles (22). Additional assumptions were that PHEV60 vehicles cost around \$15,000 more than the equivalent CV, that the average cost of an American car is

\$28,400, and that PHEV60 vehicles displace 60% of petroleum fuels as mentioned above (22). These computations led to an approximate lifetime per VMT cost of \$1.29 (\$0.80 per VKT) for PHEV60s. Obviously, these prices will differ from vehicle to vehicle and behavioral changes could result in rather different numbers—PHEV60 drivers, for instance, might very well drive less because they are generally more environmentally conscious. The relationship between the CV and PHEV costs, moreover, is heavily dependent on gasoline price and PHEV efficiency, and thus a more full analysis of this dynamic should be performed in the future. For the purposes of this argument, however, the relatively conservative approximate figures above are sufficient. To obtain the analogous lifetime per VMT costs for an MPRT system is perhaps even more ambitious given the fact that a system has never been observed over the entirety of its lifespan. A relatively accurate estimate was nonetheless obtained from the pro forma statement of a current MPRT project codeveloped by NASA and a private company by averaging the annualized cost per VMT for a hypothetical California state highway MPRT system over its full lifespan, leading to an estimated average cost of \$0.55 per VMT (\$0.34 per VKT) (John Cole, Unpublished Data). This pro forma statement included all costs involved with infrastructure installations, operation and management, financing, and any other relevant areas. Some basic cost assumptions utilized in this pro forma are that a mile of installed MPRT track costs \$20 million, that one MPRT VMT requires \$0.20 in operating costs, and that 15,000 miles of bidirectional highway would be required for a fully operational system. This last number is based on Caltrans data for extant miles of California highway. Cost estimates were made based on the MPRT prototype that is being constructed at NASA Ames (See Figure 3) and should not change beyond increasing prices of basic commodities like steel, aluminum and copper.

We have also included \$2m per mile to cover EIR, civil engineering, soil testing, foundations for the poles, electrical work and installation that could vary based on local conditions. While speculative, the cost assumptions above represent the most current possible estimates of true MPRT cost. Multiplying the above costs per VMT by 50% of annual California state highway VMT leads to the conclusion that replacement of these VMT with CVs (i.e. maintaining the status quo) would cost an average of \$109 billion per annum, replacement with PHEV60s would cost an average of \$113 billion per annum, and replacement with MPRT would cost an average of \$46 billion per annum. Carrying these calculations through over a conservative 15-year MPRT lifespan indicates that in comparison to the status quo, a PHEV60 solution would increase total transportation costs by \$68 billion, around 4%, while an MPRT solution would decrease total 15-year transportation costs by \$942 billion, a savings of approximately 55%. The calculated costs for MPRT, however, take into account a full statewide network including rural areas along state highways where MPRT solutions are significantly less cost efficient. As shown in the Table 1 below, MPRT costs become even more attractive in higher-density areas. Thus, the total cost of the hypothetical MPRT system could be significantly decreased by bypassing low-density areas and directly connecting high-density regions.

	<b>Annual cost of 50% of Calif. VMT</b>	<b>15 year savings (deficit)</b>	<b>Annual Increased value into California (assuming 25% local manufacturing, 100% local construction, and 2% local petroleum)</b>	<b>Annual Increased value into US (assuming 50% local manufacturing, 100% local construction, and 30% local petroleum)</b>
Conventional Vehicle	\$109B	0	0	0
PHEV60	\$113B	(\$68B)	\$38B	\$66B
MPRT	\$46B	\$942B	\$26B	\$36B

**TABLE 1 Projecting cost savings for 50% adoption of PHEV60 compared with a California-wide MPRT network , assuming fares of \$0.55 per mile for MPRT and 50% of drivers switch to MPRT.**

## **OBSTACLES TO IMPLEMENTATION**

Barriers to the general implementation of an idea on this scale are substantial even when the idea itself does not compete with well-established infrastructural paradigms. Given that the basic concept of MPRT is inherently different from current transportation methods, implementation on a large scale will not be an easy task. As implied above, significant, but not intractable, monetary, temporal, and political investment would be necessary even to carry out a pilot project of such a system. NASA and Unimodal Systems have already begun this process with its proposed pilot system at NASA Ames in California, and the lessons learned from this project will be invaluable in bringing this technology into the mainstream. Such a process will, however, take time and thus it is imperative that substantial amounts of resources be committed to MPRT development if the technology is to demonstrate control, safety, and reliability performance adequate for widespread implementation. In some sense, society is fighting against the clock because transportation paradigms must change rapidly given the current global rates of resource consumption and environmental degradation—if MPRT development is not heartily pursued in the present, the window of opportunity for widespread implementation may close before the technology is mature.

## CONCLUSION

This paper attempted to lay a rough technological, economic and environmental framework for why MPRT systems are ideal for utilization of renewable power generation. Not only does the MPRT concept allow for unique incorporation of renewable generation into the transportation infrastructure, but its grid-based nature also lends itself to the purpose of integrating next generation transmission and distribution systems into the general transportation architecture. Moreover, the hypothetical MPRT system exhibits:

- 1) significant cost savings compared with cars and PHEV
- 2) emissions-reduction benefits over even some of the most advanced PHEV concepts
- 3) Reduced traffic congestion and improved quality of life
- 4) Co-benefits in improving the electrical grid

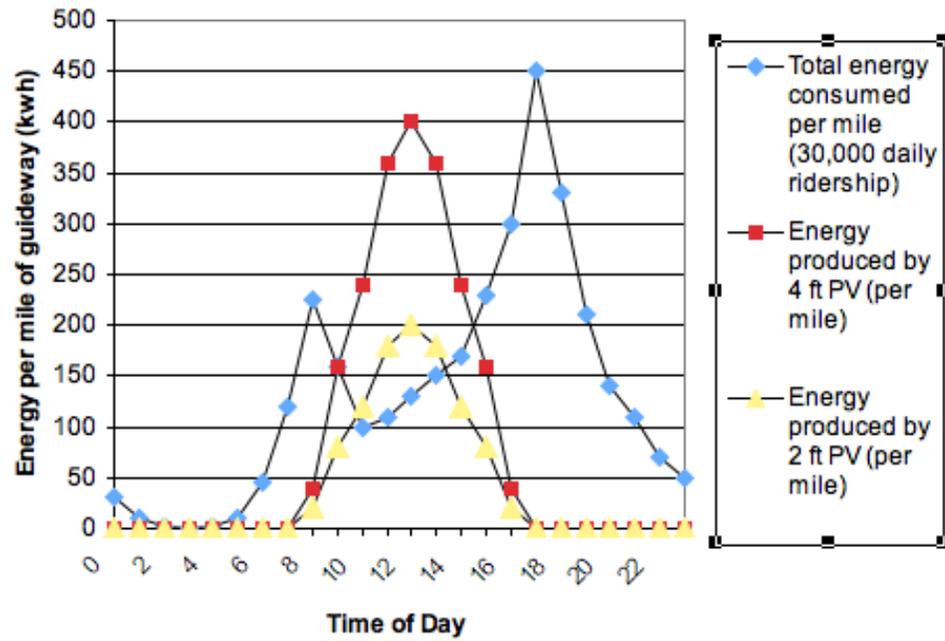
Given the substantial cost of overhauling electric generation and transportation systems facing both governments and private citizens in the near future, it would seem that an efficient solution would attempt to bundle these costs as much as possible. MPRT not only has the potential to accomplish this goal, and provides a roadmap for the most comprehensive carbon dioxide reduction potential of any technology considered here at the lowest cost while providing a significant source of jobs. It is the authors' hope that the results presented here will stimulate more research on such systems and potentially lead to the implementation of an integrated MPRT energy distribution system on a scale large enough to allow for a fuller understanding of the prospective benefits and challenges.

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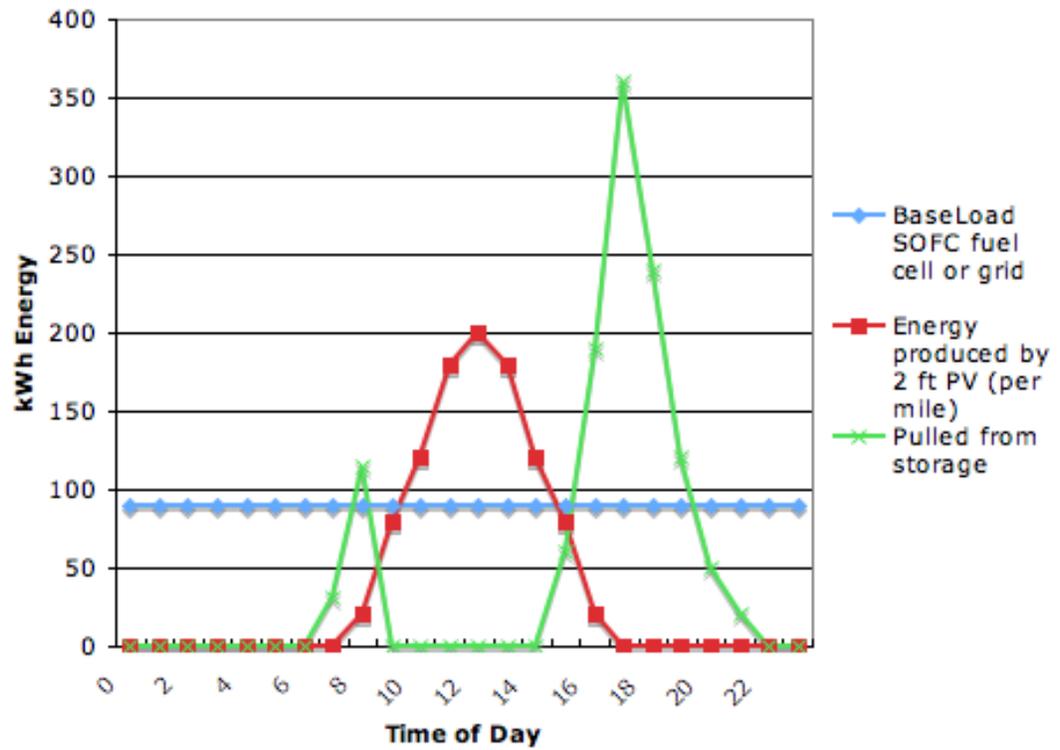
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**FIGURE 1 Production and consumption of energy in a solar-powered MPRT system.**



**FIGURE 2** Example MPRT system with 30,000 daily ridership requiring 3,156 kWh energy per day, combined with 1,000 kWh of PV and 2,156 from a SOFC fuel cell and 1,156 kWh storage system.



**FIGURE 3 – MPRT prototype at NASA Ames, Moffett Field, CA**