The Role of the Segway® Personal Transporter (PT) in Emissions Reduction and Energy Efficiency

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In December 2001, renowned inventor Dean Kamen unveiled the Segway® Personal Transporter (PT). Since then the way society looks at transportation has changed considerably. Fuel prices have risen, there is a greater awareness of the damage caused by carbon dioxide and other greenhouse gas emissions, and environmental and political forces have de-stabilized the global petroleum supply.

The Segway PT can help reduce dependence on foreign oil, use the existing energy supply more efficiently, and reduce pollution. Drivers in the United States take approximately 900 million car trips per day. The EPA estimates that half of those trips are less than five miles long and transport only one passenger—trips perfectly suited to the Segway PT. As there are many forms of powered transportation available today, this paper seeks to compare their relative impact on the environment, both in emissions created and energy consumed.

The methods for computation are explained in detail in the following sections, but let us first present a summary of statistics regarding the relative emissions output and energy efficiency of the Segway PT compared to other well-known transportation devices.

The Segway PT does not produce any emissions during operation. Its batteries do consume electricity during recharge, and we have used the emissions created during the generation and delivery as the basis of our analysis. By comparing this to the emissions generated during the refinement, transportation and combustion of automotive fuel, we can compare the Segway PT to traditional internal combustion engines. This analysis also allows us to measure relative source fuel efficiency.

Emissions Output Summary

Operating a Segway PT creates:

- 5.6 times less greenhouse gas per mile than a Toyota Prius (82% reduction)
- 14 times less greenhouse gas than the average American car (93% reduction)
- 20 times less greenhouse gas than a large Sport Utility Vehicle (SUV) (95% reduction)

Energy Consumption Summary

The Segway PT is:

- 4.5 times more energy efficient than a Toyota Prius
- 11 times more energy efficient than the average American car
- 17 times more energy efficient than a large SUV

Note: All computations based on one passenger per vehicle

I. The Segway PT and Emissions Reduction

The Segway PT is powered by custom-designed, phosphate-based lithium-ion batteries, which are safe, stable and appropriate for everyday use. There are no emissions during operation, but since the Segway PT draws energy from the power grid to charge its batteries, this evaluation is based on the emissions created by the production of the electricity consumed during recharge.

For internal combustion and hybrid engines, we must consider the emissions created during operation, as well as during the production and transportation of each vehicle's fuel. The EPA publishes emissions data for all passenger cars and trucks which incorporate all of these emissions, expressed in terms of CO_2 equivalents, which considers CO_2 as well as other greenhouse gases such as methane and nitrous oxide. Emissions for a variety of vehicles can be seen in Figure 1 (trademarks are owned by their respective companies):

Figure 1.

CO_2 Greenhouse Gas Emission Reduction if Substitution is Made with Segway PT

Vehicle	Mileage (MPG)	CO_2 Equiv. Emitted (lb/mi)	CO_2 Reduction if Segway PT substituted
Average US Passenger Car	22	1.14[2]	93%
Cadillac Escalade	15	1.61[3]	95%
Toyota Prius	55	0.45[4]	82%
Volkswagen Golf TDI (diesel)	37	0.72[5]	89%
Motorcycle	50	0.39 *	81%
Scooter	70	0.28 *	71%
Segway PT	**20 miles/charge**	**0.081**	

* Little data exist for motorcycles and scooters for gaseous emissions. In this case we have computed the actual CO_2 created by the combustion of the fuel based on reported MPG. The mass of carbon in one gallon of gasoline is 2,421 grams[6]. The molecular weight of CO_2 is 44, and of carbon is 12. CO_2 emissions from a gallon of gasoline = 2,421 grams/gallon x 0.99[7]x (44/12) = 8,788 grams/gallon = 19.4 pounds/gallon. Dividing this by the reported fuel mileage (miles/gallon) of the motorcycle/scooter gives us the pounds of CO_2 emitted per mile. This will understate the amount of emissions created by both motorcycles and scooters, as we are not considering emissions from fuel production and delivery or the equivalents for other gasses emitted.

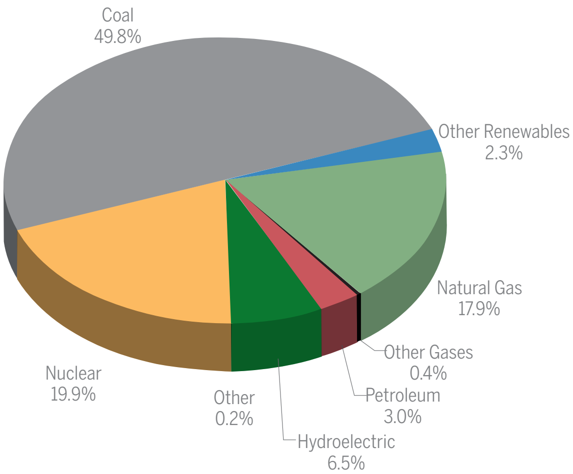
1 To compute CO2 equivalents, the relative weight of methane is multiplied by 21 and added to the total, while Nitrous Oxide is multiplied by 301. This is due to their relative impact on climate change, and is widely accepted as a way to quantify multiple greenhouse gases into one number.
2 US Environmental Protection Agency
3 http://www.fueleconomy.gov
4 http://www.fueleconomy.gov
5 http://www.fueleconomy.gov
6 http://www.epa.gov/oms/climate/420f05001.htm
7 0.99 represents the oxidation factor, i.e. 1% of the carbon in the source fuel is not oxidized

Emissions from Electricity Production

Greenhouse gas emissions from the production of electricity vary due to regional differences in source fuel. The average fuel mix for electricity production in the United States (2004 data) is shown in Figure 2.[8] Many areas where Segway PTs are more prevalent have much cleaner fuel mixes. For example, California's source fuel mix includes much more natural gas (37.6%) and geothermal (8.4%) while using very little coal.[9]

Figure 2.

Fuel Mix for Electricity Production



The average emissions for this fuel mix are 1.55 lbs of CO_2 per kWh[10], which means that a vehicle powered by electric batteries would be responsible for the creation of 1.55 lbs of CO_2 equivalents[11] for each kWh it consumed during recharging.

The Segway PT

The Segway PT is powered by two lithium-ion batteries that typically take eight to ten hours to charge and consume 1.04 kWh of energy from a wall outlet for a full battery charge[12]. The Segway PT offers its rider 16-24 miles (26–39 km) of range on a single charge. Actual range is dependant on several factors including terrain, payload, and riding style.

Using the middle of this range, the Segway PT consumes 0.052 kWh/mile (1.04 kWh/20 miles). Based on the average U.S. fuel mix for electricity production, those 52 watt-hours create 0.081 lbs of CO_2 emissions per mile (0.052 kWh/mi) x (1.55 lb. of CO_2/kWh) = 0.081 lb. of CO_2. This is fourteen times less greenhouse gases emissions than for the average American car driven the same distance.

II. The Segway PT and Energy Efficiency

What Is True Energy Efficiency?

While reducing emissions is extremely important, so is the efficient use of energy resources. This benefits the user in the form of reduced operating costs, and society as a whole by reducing our total energy demand and dependence on oil.

Energy efficiency is a complex computation, and is often oversimplified into terms like miles per gallon (MPG) or liters per 100km (l/100km). To gain a true understanding of energy efficiency, one must consider the energy consumed during the production and transportation of the fuel, as well as the energy content of the fuel itself. In the case of distributed electricity, one must consider both the electricity consumed during operation and the transfer losses that occur between the power plant and the wall outlet.

[8] Energy Information Administration, http://www.eia.doe.gov/fuelelectric.html
[9] Speech by Jim Boyd, California Energy Commission, Dec. 7, 2006, San Diego, CA
[10] www.energystar.gov
[11] Several other gases are emitted during the combustion of fossil fuels that could contribute to climate change. CO2 is by far the largest component of the gaseous emissions of electricity production, and any contributions the other gases (methane, nitrous oxide, etc.) have on this number are insignificant.
[12] Segway Inc. internal testing

Energy density can be compared among different fuels using mega-joules of energy per kilogram (MJ/kg). For vehicles and personal transporters, energy efficiency can then be expressed in terms of distance covered per mega-joule of fuel consumed (miles/MJ); a higher number being better.

Gasoline-Powered Vehicles

Pump-delivered gasoline has an energy density of 46.7 MJ/Kg[13]. The production and delivery process is between 83% and 86% efficient depending on the grade and composition[14]. Therefore, it takes between 54 and 56 mega joules of crude oil to produce a kilogram of gasoline. Since a gallon of gasoline weighs about 2.72 kilograms[15], it takes about 150 MJ worth of crude oil to deliver one gallon of gas at the pump.

Diesel fuel has an energy density of 45.9 MJ/Kg.[16] The production and delivery process for diesel fuel is 87-89%[17] efficient, and a gallon weighs about 3.23 kg. Therefore it takes about 168 MJ worth of crude oil to deliver one gallon of diesel at the pump.

Energy Efficiency of Battery Powered Vehicles

Electricity is produced by a variety of methods including the burning of fossil fuels, hydroelectric, nuclear, and wind power. The efficiency of the electrical power production process is dependant on the source fuel, but for the average mix for the United States, the average efficiency is 34.3%[18]. In other words, the equivalent of one kWh of source fuel is consumed in order to produce 343 Wh of electricity. In addition, the transfer process along the power grid is 92% efficient[19], making the "well to wall" generation and delivery of energy 31.6% efficient (.92 x .343=.316).

One kWh is equivalent to 3.6 MJ of energy. Based on 31.6% efficiency, (1 kWh/31.6%) (3.6 MJ/kWh) = 11.4 MJ of source fuel energy are required to deliver one kWh of electrical energy at a residential power outlet. Energy usage efficiency for a battery powered vehicle can then be determined by dividing the range of the vehicle on one charge in miles by the measured electrical consumption during recharge in kWh and then dividing the result by 11.4 MJ/kWh.

Energy Efficiency of Cars and Trucks

The average passenger car in the United States gets 22.4 MPG[20]. Based on the energy required to produce one gallon of gasoline at the pump (150 MJ), the average car in the United States travels 0.15 miles per mega-joule. It should be noted that some car journeys are multi-passenger, so energy efficiency will be higher in those cases.

The energy efficiency of a variety of vehicles occupied by one person can be seen in Figure 3:

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13 *Well-to-Wheel Studies, Heating Values, and the Energy Conservation Principle*, 29 October 2003, Ulf Bossel,

14 *Well-to-Tank Energy Use and Greenhouse Gas Emissions of Transportation Fuels – North American Analysis*, General Motors Corporation Argonne National Laboratory, p. 159

15 *Fuel From Farms: a Guide to Small Scale Ethanol Production.* U.S. Dept. of Energy. May 1980. Page D-3.

16 *Well-to-Wheel Studies, Heating Values, and the Energy Conservation Principle*, 29 October 2003, Ulf Bossel,

17 *Well-to-Tank Energy Use and Greenhouse Gas Emissions of Transportation Fuels – North American Analysis*, General Motors Corporation Argonne National Laboratory, p. 159

18 Lawrence Livermore National Laboratory, 2001

19 *Well-to-Tank Energy Use and Greenhouse Gas Emissions of Transportation Fuels – North American Analysis,* General Motors Corporation Argonne National Laboratory, Vol 3, p.33

20 USDOT, Bureau of Transportation Statistics, 2004

Figure 3.

Energy Efficiency by Vehicle Type

Vehicle	Mileage (Low)		Mileage (Average)		Mileage (High)	
	"City" mileage[21], or low end of battery range	Energy Efficiency (miles/MJ)	Combined mileage[22], or middle of battery range	Energy Efficiency (miles/MJ)	"Highway" mileage[23], or high end of battery range	Energy Efficiency (miles/MJ)
Cadillac Escalade	13	0.09	15	0.10	17	0.11
Average U.S. Passenger Car	n/a	n/a	22	0.15	n/a	n/a
Volkswagen Golf TDI	33	0.20	37	0.22	44	0.26
Motorcycle	40	0.27	50	0.33	60	0.40
Toyota Prius	51	0.34	55	0.37	60	0.40
Scooter	60	0.40	70	0.47	80	0.53
Segway PT	**16**	**1.35**	**20**	**1.69**	**24**	**2.02**

For example, The Toyota Prius, one of the most widely recognized "high-mileage" cars, has an average fuel economy of 55 MPG. If 150 MJ are required to produce and deliver one gallon of gasoline to the Prius's tank, this yields an energy efficiency of 0.37 miles/MJ (55 ÷ 150).

Motorcycles

The average motorcycle gets 50.1 MPG[24], yielding an energy efficiency of 0.33 miles/MJ. It should be noted that the vast majority of motorcycle and scooter journeys are single-passenger.

Scooters

Gas-powered scooters vary in their mileage, but modern four-stroke scooters generally fall in the 60-80 MPG[25] range. Using the upper limit of this range yields an energy efficiency of 0.53 miles/MJ.

Segway PT

Under normal conditions the Segway PT consumes 1.04 kWh[26] of electricity in order to fully charge its lithium-ion batteries. The range of a fully-charged Segway PT is 16 to 24 miles, depending on factors such as terrain and riding style. Using the middle of that range, the Segway PT uses 1040 Wh of electricity from the wall outlet to go 16 miles, which yields an efficiency of (16 mi/1.04 kWh delivered)/(11.4 MJ source energy/kWh delivered) = 1.69 miles/MJ.

Using this range, the Segway PT travels 4.5 times farther per MJ of source fuel than the Toyota Pruis, and 3.6 times farther than even the most efficient gas-powered scooters.

Conclusion

When used as intended, the Segway PT can drastically reduce greenhouse gas emissions and substantially increase energy efficiency by replacing short-distance single-occupancy car journeys. Its compact yet robust design makes it suitable for a variety of everyday uses and commercial applications, allowing riders to cover distances which would have previously required the use of a traditional vehicle.

22 http://www.fueleconomy.gov
22 http://www.fueleconomy.gov
23 http://www.fueleconomy.gov
24 USDOT, Bureau of Transportation Statistics, 2003
25 Claimed mileage from various manufacturers
26 Segway Inc. internal testing

John David Heinzmann, a Propulsion Engineer at Segway, Inc., holds bachelor's and master's degrees in Mechanical Engineering. He began working with DEKA Research and Development Corp in 1995 and moved to the Segway project in 2000. At Segway, he led the development of the power electronics to drive the wheel motors of the Segway Personal Transporter. While at Deka he was involved with the development of power electronics and control algorithms for the Independence™ iBOT™ Mobility System (balancing wheelchair). In a prior role, he was an engineering contractor for the R&D center of Pacific Gas and Electric Company testing and analyzing the performance of advanced energy systems including photovoltaic power generating test facilities and their power conversion electronics, a superconducting magnetic energy storage system, the AC and DC power distribution system for the BART (Bay Area Rapid Transit) trans-bay tube, and a 40 ton "AC Battery" system, and developing a super-capacitor energy storage system for a small uninterruptible power supply.

B. Michael Taylor is a Product Manager at Segway Inc. He has been with Segway since 2001 and has led product marketing efforts for the company's Personal Transporters with a focus on urban commuting. Prior to Segway he led marketing and development for advanced athletic footwear technologies at companies including Reebok International and Puma AG.