Social Ramifications of Autonomous Urban Land Vehicles

Tyler C. Folsom
QUEST Integrated, Inc.
Kent, WA, USA
tyler@tfolsom.com

Abstract—**Autonomous vehicle technology may arrive much sooner than most people expect and it has profound implications for transportation. The technology facilitates a rail-less personal rapid transit (PRT) system using both public and private vehicles. Road traffic fatalities and injuries may decline by one to two orders of magnitude. A PRT system can provide mobility to the blind, elders suffering from dementia, children and the intoxicated. The system can make use of existing infrastructure, reduces urban sprawl and eases congestion. Autonomous vehicle based systems can improve fuel efficiency. The technology presents a window of opportunity for a new mode of transportation that obtains efficiencies of up to 0.25 l/100 km (1000 mpg equivalent), reducing U.S. petroleum consumption by up to 16%. The U.S. carbon savings could reach the equivalent of 12 trains of 100 coal cars daily.**

Keywords-Autonomous vehicles, personal rapid transit, traffic safety, fuel efficiency, mobility, global warming, people mover, pod car.

I. Introduction

Most of what has been written about the social implications of autonomous vehicles is concerned with military vehicles, particularly aerial vehicles [1]. By contrast, this paper addresses the implications of civilian urban land vehicles. When the military designs land vehicles, it assumes an unknown or hostile environment. If the infrastructure instead cooperates with the vehicles and the routes are fully known, autonomy becomes much easier.

In the next 5 to 15 years, driving one's own car will start to disappear. The technology is on hand to let the car drive itself [2]. Cars that can drive themselves can easily be put under the control of a traffic management computer, which can greatly reduce accidents and congestion.

There are three levels of vehicle autonomy:

1. Improved driver assistance.
2. Autonomy only on a reserved roadway separated from other vehicles.
3. Full autonomy on city streets.

The first level is happening now. It includes cruise control, collision avoidance, lane following, monitoring blind spots, intelligent cruise control and self-parking systems. Commercial systems are available from several vendors.

The second level could be in place within six years. The 2005 DARPA Grand Challenge race offered a prize of $2 million to the team that could cross 212 km of the Mojave desert the fastest. This was done mostly on dirt roads that were closed to all other traffic. The location of the route was not announced until the morning of the race. Five vehicles finished.

The third level is ten to twenty years out. The 2007 DARPA Urban Challenge tested the ability of fully autonomous vehicles to drive in traffic. The event was held on an abandoned military base in Victorville, California. About 50 race cars drivers were hired to provide the traffic. Google is in the process of demonstrating autonomy in the San Francisco area [3].

Liability issues are an important consideration in the introduction of autonomous vehicles. As the driver becomes less important, liability may shift from the driver to the manufacturer, providing a disincentive to hybrid driver / computer assistance systems [4]. A system that has no dependency on the driver may produce less legal exposure for manufactures. This paper assumes that the legal issues have been resolved and examines subsequent social impacts.

Due to liability issues, the system will likely be deployed in China before it is accepted in the United States. China is the world's leading producer and consumer of electric vehicles, most of which have two wheels [5]. China is committed to electric vehicles and the system envisioned in this paper would be a good fit to China.

II. Safety

A. Traffic accidents

Automobiles are so common in our lives that we seldom think of their danger. In the U.S. in 2007 there were 37,248 fatal crashes resulting in 41,059 deaths. These included 21,647 drivers, 8,657 passengers, 5,154 motorcyclists, 4,654 pedestrians and 698 bicyclists [6] .

In 2006, U.S. motor vehicle traffic-related injuries resulted in 43,664 deaths [7]. This compares to 30,896 deaths from firearms injuries, 17,034 from homicides and 0 from terrorism [8]. There were 2,575,000 traffic injuries at an estimated economic cost of $230 billion [6].

For 2003-2007, deaths in California traffic alone exceeded American deaths in the Iraq war in each of four age groups between 18 and 50 [9]. For the 20th century, 667,701 American troops have died at war and 3,070,325 Americans have died on our roads [10,11].

Worldwide, an estimated 1.18 million people died from road traffic crashes in 2002 [12]. This accounts for 2.1% of all global deaths and ranks as the eleventh leading cause of global deaths. Between 20 and 50 million people are injured each year from road crashes. Projections indicate that road traffic injuries could reach third place as a global burden of disease and injury by 2020 [12].

In 2006, alcohol was involved in 41% of U.S. fatal crashes and 1.46 million arrests were made for driving under the influence of alcohol or narcotics [6]. The United States has tried prohibiting both, but people continue to use them and when they do, driving home is the most convenient choice. Driving while intoxicated is a structural feature of the automotive transportation paradigm and there is no hope that it will ever be eradicated through education or coercion.

In head-on crashes between SUVs and passenger cars, five passenger car occupants die for every SUV death [13]. This results in an arms race, where people buy a heavier car than they need based on perceived safety. The weight bloat could be broken by segregating motorcycles and light passenger cars from heavier vehicles. A rapid transformation to light vehicles could happen if autonomous vehicle guideways were designed for light vehicles alone, with heavy vehicles physically incapable of operating on these guideways.

B. A Rail-less PRT

Personal Rapid Transit (PRT) was designed in the 1970's, but the first PRT system was not deployed until 2010. PRT is based on small vehicles, each carrying 1 to 6 people. There are no schedules. Vehicles are autonomous, run on reserved guideways and are available on demand. They typically run on rails and take the most direct route from origin to destination without stopping at intermediate stations. Every station is offline, with a short side track connection to the main line [14].

An autonomous road vehicle can be operated as a rail-less PRT. The "rail" becomes a line painted on a paved roadway. Robot line-following is a standard technique and can be done with a simple camera or light sensor. The painted "rail" enables much faster switching times than steel rails. Fast switching time decreases the spacing required between vehicles and thus increases system capacity. On a PRT system, all vehicles operate on the main line at full design speed. There must be no intersections. Thus a freeway lane, barricaded from other vehicles, can become a PRT guideway.

Manual driving requires space between vehicles for driver reaction time and brake application time in emergencies. In an autonomous system, there is no driver and thus cognition time is a few milliseconds. All vehicles are under computer control and have access to the state of the vehicle ahead. A trailing vehicle knows that the lead vehicle is about to slow, accelerate or turn before the action is undertaken. It could thus be feasible for vehicles to operate bumper to bumper at full speed. Driver error is eliminated as an accident cause. Remaining accident causes would be limited to system malfunctions or physical mishaps such as flat tires or ice or debris on the roadway. Such occurrences may be mitigated by vehicles physically coupling to each other.

C. Autonomous Vehicle Safety

A system of computer controlled vehicles is likely to have safety characteristics more similar to autonomous trains than to individually controlled motor vehicles. It is instructive to examine the safety record of autonomous trains.

In France, an autonomous commuter rail system has been operating in the city of Lille since 1983. During peak periods, the trains run on headways of one to two minutes [15]. This system is organized in two lines, includes 60 stations, extends over 45 km and carried 86 million passengers in 2007 [16]. It has a peak speed of 80 kph and its average speed is 32 kph. The system has been replicated at a smaller scale in Jacksonville, Paris airport, Toulouse, Chicago and Taipei [17].

In 2005 and 2006 there were no deaths on the Lille metro or any other metro in France. The total number of injuries for 27 metro lines throughout France were 22 in 2005 and 26 in 2006 [18]. We can thus estimate an annual accident total for the Lille metro of no deaths and two injuries. Lille is the largest city of the Nord Departement, a region of 2,554,449 inhabitants. For 2007 there were 2,657 motor vehicle injury accidents in the region resulting in 103 deaths and 3,407 injuries [19].

To make a rough comparison of the accident rates of motor vehicles to those of an autonomous vehicle system, note that there are 40 million cars and trucks in France out of a population of 61.6 million [20]. Assuming the same ratio in the Lille region predicts 1,659,000 cars there. The French automobile occupancy rate is 1.8 [21]. French urban residents typically make 3.5 to 4.0 trips per day [22]. The upper figure yields an estimate of 4.36 billion drivers and passengers using motor vehicles yearly, which is 51 times as many as metro passengers. The non-fatal injury ratios would be expected to be similar. Instead, the ratio is 1700:1. We can thus conclude that motor vehicles are 33 times as dangerous as autonomous vehicles on a reserved path. Metro accidents will happen, but when they do, they are news. Car accidents rarely make the national news.

This calculation is consistent with the finding that travel by rail is more than an order of magnitude safer than road travel. Data for death rates from different travel modes are given in Table 1 [23].

Table 1. Death risks for different travel modes in the EU for 2001/2002

	Deaths / billion person km	Deaths / billion person travel hr
Rail	0.35	20
Road (total)	9.5	280
Motorcycle	138	4400
Cycle	54	750
Foot	64	250
Car	7	250
Bus	0.7	20

Vancouver BC has been operating the autonomous Skytrain since 1986 with 133,000 weekday passenger trips in 1994. A study of accident rates in 1995 gave identical statistics for the Lille and Vancouver systems of 2.8 incidents, 0.0 deaths and 0.0 injuries per 1,000,000 vehicle revenue km [24]. Table 2 shows that these autonomous train systems are considerably safer than Light Rail Transit (LRT) or Rapid Rail Transit (RRT) systems. By contrast, the U.S. motor vehicle accident rate for the same period was 2.726 deaths and 330.3 injuries per 1,000,000 km [6]. Using the U.S. average number of persons per vehicle of 31.3 for commuter rail and 1.57 for cars one could compute relative safety estimates per person [25]. Such statistics would be misleading, since they compare different countries. It is sufficient to note the indication that autonomous vehicles produce a safety advantage of orders of magnitude.

Table 2. Transit safety (Per million vehicle revenue km)

System	Incidents	Injuries	Fatalities
Vancouver	2.8	0.0	0.0
Lille	2.8	0.0	0.0
LRT systems	39.3	30.5	0.1
RRT systems	12.4	11.0	0.1

III. OTHER EFFECTS

In addition to a huge improvement in traffic safety, the transition to autonomous vehicles will have numerous other effects. Total computer control of personal transportation topples many barriers.

A. Greater access to transportation

Some handicaps, such as blindness, preclude driving. A fully autonomous vehicle only requires the rider to be able to select her destination. It thus open new horizons to individuals who currently need to depend on others for their transportation.

Dementia can occur with aging. When it does, it produces a situation where an elder becomes an unsafe driver. This can result in injury or death to the driver or others. Individuals must either be capable of recognizing the situation and surrendering their drivers license or doctors or relatives must force this outcome. This is a stressful time for everyone involved. Loss of mobility isolates elders. With autonomous vehicles, there is no need for elders to lose mobility. Prime candidates for the first small scale autonomous vehicle systems may be retirement communities.

At the other end of the age spectrum, autonomous vehicles grant greater mobility to children. Parents or teachers can set a non-overridable destination. School buses would become obsolete. Parents no longer need to be chauffeurs to deliver their children to sporting events or after school activities. This could have the negative effect of decreasing the involvement of parents in their child's activities.

Autonomous vehicles provide safe and convenient transportation for the inebriated. A computer controlled system may be the only effective solution to drunk driving. In some ways, this is similar to the pre-automotive age in which a horse could find its way home with minimal assistance from the rider.

B. Public Transportation

The proposed system incorporates both public and private transportation. When a city decides to install a level 2 system (autonomous only on restricted lanes), the city sets up the lanes and buys thousands of public vehicles. This is the same paradigm that a city would use to install a light rail system. The public vehicles must be boarded only at stations adjacent to the entry ramps for the restricted lanes. Disembarkation would be similarly limited.

The stations at the entrances to the autonomous lanes would have gated entries to admit private vehicles. A private vehicle wishing to operate on the restricted lane would have to pass a stringent test demonstrating its ability to operate under computer control and be completely compatible with the public vehicles. The vehicle is then issued an encrypted code which it presents to the electrical gateway and is allowed to operate on the system under computer control. After passing the gate, all manual control of the vehicle is physically disabled. After the vehicle exits from the system, manual control is restored at an exit gate.

This design fills the gaps at the closest station to the trip origin and the closest station to the destination. A single private vehicle makes the entire journey. It operates under manual mode on city streets at either end and autonomously in the middle. The existence of the public system gives people an incentive to buy their own vehicle for a new mode of transportation. As the number of private vehicles increases, the city's share of system cost decreases.

In our current transportation system, a private car is much more convenient than a public bus. In the proposed transportation system, public transportation may be more convenient than private transportation. Both modes would be based on small driverless vehicles. Either mode is available on demand. Both travel at the same speed on the most direct route. When level 3 (full autonomy) is reached, a public vehicle can be summoned by a phone call. A private vehicle is either boarded where it was parked, or if that is too distant, summoned by a phone call. Public transportation resembles a fleet of driverless taxicabs. Maintaining one's own vehicle carries the problem of finding parking for it.

C. The Urban Landscape

A typical U.S. suburban business district devotes an enormous amount of land to parking. This causes cities to sprawl. The large area of impermeable surfaces leads to increased runoff following storms. Surface water runoff has been identified as the prime contributor to decline of water quality in Puget Sound [26]. This in turn leads to declining populations of salmon, orca whales and other marine life.

Parking lots are built to accommodate peak demand and during a 24 hour period are rarely full. With an autonomous system, fewer vehicles are required. A public vehicle can deliver a rider to her destination, then drive itself to the next person requesting transportation. Less parking is required for autonomous vehicles. A private vehicle can drop the rider at his destination and then drive itself several kilometers to park.

When full autonomy on city streets is possible, deliveries can be made without a driver. This could have a major impact on restaurant food delivery.

D. Reduced Congestion

Vehicles under computer control need very little spacing, with the result that freeway capacity increases [2]. If the system is built with small vehicles, 2 or 4 lanes can fit in the space required for a single freeway lane or railroad track. Thus congestion is reduced and the result may be that no new urban freeway lanes need to be built.

In a PRT system, vehicles on the main line always travel at design speed. A vehicle changes its speed only on exit or entry ramps. Vehicles entering the system will be precisely timed so that they have a free spot into which to merge. If the system saturates, no new vehicles will be admitted, but those on the system continue at full speed. Any interchanges would be served by parking buffers so that vehicles changing routes always have a space available for merging.

E. Employment

The effect on employment is unclear. Small driverless vehicles would replace buses. The bus drivers may find work as attendants or fare collectors for a public transportation system based on autonomous vehicles. The experience with the Lille autonomous train is that a fully automated station encourages crime [17]. Thus the Lille transit authority has hired people whose job is to provide a human presence in the station and provide help to anyone needing it.

New jobs would be created in manufacturing the vehicles and their electronics. These may displace jobs in other vehicle sectors. If little new highway construction is needed, there could be a decline in construction jobs. On the other hand, implementation of an autonomous system will require construction of barriers and gates to exclude manually driven vehicles from autonomous lanes. There will also be a need to construct parking buffers and manual/autonomous transition stations at every entry and exit point to the autonomous guideways. Many cities outside the U.S. do not have urban freeways and would require construction of new guideways.

IV. Fuel Efficiency

Computer control of vehicles allows decreased following distances. As vehicles travel in the slip stream of those ahead, fuel consumption goes down. This effect can be particularly dramatic for freight trucks, which average only 39 l/100 km (6.0 mpg) [27]. Greater efficiency could be obtained by increased use of rail systems to move freight.

The expected outcome for autonomous traffic systems is that they are built using existing automobiles. As autonomy becomes a real option, there is a transition window of a few years offering a chance to invent a new transportation mode other than trains, buses, cars or bicycles. This system would be an urban people mover. It is not suited for freight or rural transportation.

The power required to move a vehicle is the sum of energy changes needed to overcome rolling resistance (W_R) and aerodynamic drag (W_D) which are given in (1) and (2) [29].

$$dW_R/dt = C_V/\eta \; \Sigma m \cdot g[C_R+s/100+a/g(1+m_W/\Sigma m)] \quad (1)$$

C_V: Speed of vehicle
η: Overall mechanical efficiency of transmission
Σm: Total mass of vehicle, rider and baggage
g: Gravitational acceleration
C_R: Coefficient of rolling resistance
s: Upslope (%)
a: vehicle acceleration
m_W: Effective rotational mass of wheels

$$dW_D/dt = 0.5 \; C_V/\eta \; C_D \; A \; \rho \; (C_V+C_W)^2 \quad (2)$$

C_D: Aerodynamic drag coefficient
A: Frontal area of vehicle and rider
ρ: Air density
C_W: Headwind

To minimize the energy expended against rolling resistance, one can reduce vehicle mass, speed, starts and stops and avoid hills. The PRT design minimizes starts and stops. The most effective variable would be the mass. The model T Ford weighed 545 kg and had a 15 kW engine [29]. In 2003, EPA reported that the average U.S. car weighed 1820 kg [30]. The average American male weighs 86 kg [31]. Reducing total mass from 1900 kg to 190 kg reduces rolling weight power consumption ten times. With the computer controlling all vehicles, accidents become rare and the SUV has almost no safety advantage over a motorcycle. An autonomous vehicle system could be an opportunity to build a transportation system around motorcycle sized three- or four-wheeled vehicles.

The other power consumer is aerodynamic drag, which is critical for light vehicles. For a car, the cross-over point between the dominance of rolling resistance and drag comes at about 60 kph. For a bicycle, the cross-over point is at 20 kph [32]. Drag can be decreased by streamlining the vehicle and minimizing frontal area. Eliminating headwinds by enclosing the guideway in a tube and inducing tailwinds further reduces drag. However, the most critical variable is vehicle speed. If the design speed were cut from 100 kph to 50 kph, the aerodynamic power requirements fall by a factor of 8. A light rail vehicle designed to travel at 100 kph has an effective speed of less than 50 kph when stops at stations and passenger wait times are included. Thus a PRT vehicle traveling at a constant 50 kph is faster than the train. Automobiles seldom travel at full speed in congested urban conditions.

The vehicle that minimizes power consumption looks like a three wheeled recumbent motorcycle enclosed by a streamlined body. It might be 0.8 m wide, 1.2 m high and 3 m long. A two person version might double the length. These pod cars would be primarily designed for commuting. If used by a family or group, several pods can be electronically linked to each other and function as a single vehicle. A shopper can slave a second vehicle to carry purchases.

Energy consumption can be reduced by a factor of 10 beyond what the automotive industry has in mind. Fuel efficiencies of 0.5 to 0.25 l/100 km (500 to 1000 mpg equivalent) are possible when the entire system is designed for that objective. Table 3 gives the energy requirements of various vehicles [32].

Table 3: Energy consumption at 50 kph (MJ/km/person)

Mode	Energy consumption
One person pod car	0.046
Bicycle	0.126
Train and riders	0.469
Car and five riders	0.502
Car and driver @ 6.2 l/100 km	2.26

Any discussion of fuel efficiency must reference the speed. When examining other cases, they must be scaled to the design speed using (1) and (2). With appropriate assumptions of vehicle characteristics, theoretical fuel consumption is plotted in Figure 1. This can be compared with historical data.

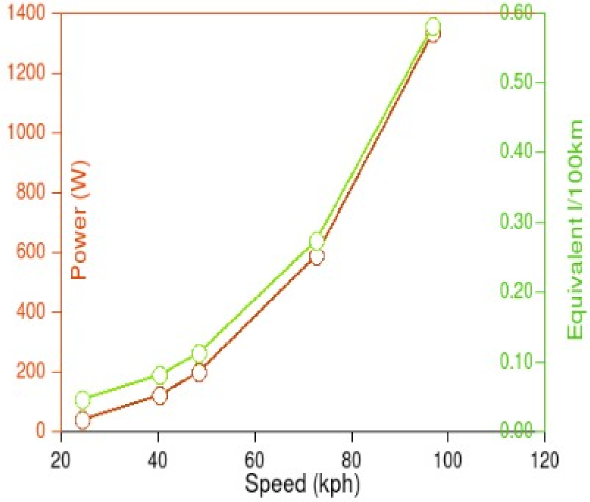

Figure 1. Power dependency on speed.

The winner of the 2006 Supermileage event held by the Society of Automotive Engineers (SAE) was a student team from the University of British Columbia. They achieved 0.075 l/100 km (3145 mpg) in a gasoline powered vehicle, apparently at speeds of 20 kph [33,34]. The fuel efficiency would not be as good at 50 kph but it is difficult to estimate an approximate mileage at that speed.

In 1980, Douglas Malewicki achieved 1.5 l/100 km (157 mpg) from a faired three-wheel motorcycle driven on California freeways. The vehicle weighed 105 kg and was powered by a 1900 W gasoline engine [35]. The mileage can be expected to improve at lower speed.

Most major automobile manufacturers have plans for an electric or plug-in hybrid vehicle. Electric cars are more efficient than gasoline cars and can travel farther on equivalent amounts of energy. However, the energy density of gasoline is much higher than what can be achieved with batteries. Electric cars may carry 500 kg of batteries and thus weigh more than a gasoline car. Since pod cars are light and do not require extended range they are ideal candidates for electric power. A lithium ion battery weighing 10 kg or less should be sufficient to provide 30 km of range. A light battery makes it practical to refuel by swapping batteries.

In 2009 the U.S. consumed 18,771,000 barrels of oil per day, with 52% coming as imports and 9 million barrels going to motor gasoline [36]. Total vehicle kilometers were just under 5 trillion, with 65% classified as urban and 35% as rural [37]. Thus urban transportation accounts for 6 million barrels of oil per day.

In 2001, trips to the workplace accounted for 19% of U.S. personal travel distance [38]. The largest sector was social and recreational trips, accounting for 30%. Family and personal business accounts for 19% and shopping for 14%. The typical driver makes 3.35 trips per day, totaling 52.7 km. The average trip to work is 19.5 km and takes 25.5 minutes, which is an average speed of 45.9 kph. These trip lengths are solidly within the range that the proposed system is designed to handle.

At full deployment, the people mover might replace half of U.S. urban motor vehicle trips. About 3 million barrels of oil per day would be replaced by the energy needed to run the pod cars, which would come from electricity. This accounts for 16% of U.S. oil consumption or 31% of U.S. oil imports.

The pod cars can be run from electricity, which in the best case scenario come from renewable resources. In the worst case, the electricity is generated from coal. Assume that the pod cars require one tenth the energy of the cars that they replace. Replacing one-tenth of 3 M barrels of oil by the equivalent energy from coal produces carbon savings of 146,000 metric tons daily. This is equivalent to 12 trains of 100 coal cars.

V. Conclusion

A properly designed urban people mover system based on light single occupancy vehicles has numerous advantages. In the U.S. alone it could save thousands of lives annually and free billions of dollars spent on caring for victims of traffic accidents. Its convenience could surpass the automobile and provide mobility to people who are unable to drive. It can reduce urban congestion and the sprawl caused by parking lots. Wide scale acceptance could reduce U.S. oil consumption by 16% and eliminate 146,000 metric tons of carbon daily.

The advantages of the people mover system call for a serious development program by either a private company or a national government. On May 25, 1961 President Kennedy set the goal of landing a man on the moon by the end of the decade. By 1968 the dream was reality. A similar effort could put people mover systems in place in a similar time frame. The payoffs from developing people mover systems could exceed those from the space program.

References

[1] A. Finn and S. Scheding, Developments and challenges for unmanned autonomous vehicles, Berlin, Springer-Verlag, 2010.

[2] M. Campbell, M. Egerstedt, J.P. How and R.M. Murray, "Autonomous driving in urban environments: approaches, lessons and challenges", Phil. Trans. Roy. Soc. London, vol. A368, pp. 4649-4672, Oct. 2010.

[3] S Thrun, What we are driving at, Google Blog 10/09/2010. Downloaded Nov 16, 2010.

[4] N Kalra, J. Anderson, and M. Wachs, Liability and Regulation of Autonomous Vehicle Technologies, Berkeley, University of California, April 2009.

[5] IDTechEx, Electric Vehicles Forecasts, Players and Opportunities 2005-2015, Cambridge, MA, 2005.

[6] National Highway Traffic Safety Administration (NHTSA), Traffic Safety Facts, Washington, 2008

[7] National Vital Statistics Report, Volume 57, Number 14, Washington, April 2009

[8] FBI, Crime in the United States, 2006, Washington, Sept 2007.

[9] http://cacrash.org/IDeaths.html Downloaded Nov 16, 2010.

[10] http://www.homeofheroes.com/moh/memory/statistics.html Downloaded Nov 16, 2010

[11] www.saferoads.org/federal/2004/TrafficFatalities1899-2003.pdf Downloaded Nov 16, 2010.

[12] World Health Organization, (WHO) World report on road traffic injury prevention: summary, Geneva, 2004.

[13] U.S. Dept of Transportation (DOT), Injuries due to vehicle mismatch, Washington, 2010.

[14] J. E. Anderson, "What is Personal Rapid Transit?", University of Washington, 1978

[15] Personal communication at Transpole Control Center, Lille, France, July 2008

[16] S.Rabuel, Les transports publics guidés en France : Données 2005 - métropole hors Paris/Île-de-France,

[17] www.fr.wikipedia.org, Metro de l'agglomeration de Lille, downloaded Nov. 14, 2010.

[18] Service Technique des Remontées Mécaniques et des Transports Guidés "Rapport accidents metros 2003-2006", Saint-Martin d'Hères, France, 2007.

[19] Sécurité routière, "Observatoire national : statistiques des accidents L'accidentologie locale - Données Générales : NORD (59)", 2009.

[20] WHO, Global status report on road safety, Geneva, 2009.

[21] Eurostat, 2001: Transport and Environment: Statistics for the Transport and Environment Reporting Mechanism (TERM) for the European Union, data 1980-1999, Luxembourg, 2001.

[22] M.O. Gascon, Enquestes de mobilitat com a eina per a l'anaalisa i la planificacio, Sabadell, Spain, 2007.

[23] European Transport Safety Council, Transport safety performance in the EU a statistical overview, Brussels, 2003.

[24] L. D. Shen, J. Huang and F. Zhao, Automated People Mover Applications: A Worldwide Review, 1995

[25] U.S. Department of Energy, "Transportation Energy Data Book", Washington, June 2008

[26] Puget Sound Partnership, Puget Sound Action Agenda, Olympia, WA, 2009

[27] U.S. Energy Information Administration (EIA) , http://www.eia.doe.gov/oiaf/servicerpt/table9.pdf, downloaded Nov 16, 2010.

[28] F. R. Whitt and D. G. Wilson, Bicycling Science, 2nd ed, Cambridge, MA, 1983.

[29] B. R. Kimes, The Cars that Henry Ford Built, Automobile Quarterly, 1978.

[30] D. Hakim, Average U.S. car is tipping scales at 4,000 pounds, NY Times, May 5, 2004.

[31] Advance Data from Vital and Health Statistics, No. 347, Oct 2004.

[32] D. G. Wilson, Bicycling Science, 3rd ed, Cambridge, MA, 2004

[33] Time magazine, Best inventions of 2006 - Easy rider.

[34] Personal communication. at UBC, Vancouver, 2007.

[35] A.C.Gross, C.R.Kyle and D.J. Malewicki, "The aerodynamics of human-powered land vehicles", Scientific American, New York, Dec 1983.

[36] EIA, http://www.eia.doe.gov /energyexplained/ downloaded Nov 16, 2010.

[37] DOT, Traffic Volume Trends, Washington, 2008.

[38] P. S. Hu and T.R. Reuscher, Summary of Travel Trends. DOT, Dec 2004.