Energy and Autonomous Urban Land Vehicles

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***Abstract*—The U.S. urban transportation system is largely based on internal combustion engine (ICE) automobiles, with the result that 93% of energy is expended on moving vehicle mass and 7% on moving people. There are indications that a transport revolution may be under way, with significant use of electric energy; if so, it is technically feasible to simultaneously incorporate autonomous or semi-autonomous behavior in the new vehicles. An automated system has the potential to drastically reduce traffic accidents, removing one of the causes for vehicle bloat. Small, aerodynamic, automated electric vehicles could run on a tenth of the energy currently used to power ICE automobiles. An automated system using existing infrastructure is technically feasible today if full automation is restricted to reserved lanes and the vehicles are operated under manual control in other places. An automated system could reduce congestion, blur the distinction between public and private transportation, provide greater access to transportation and transform the urban landscape. The non-technical barriers to automation are greater than the technical barriers. 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, traffic safety, fuel efficiency, mobility, global warming, pod car, automated highway system, personal rapid transit.

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 effects that civilian urban land vehicles could have on energy consumption. 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.

An autonomous vehicle senses its environment and controls itself to safely reach its destination without driver intervention. An automatic vehicle follows the directions of an off-board computer. An autonomous vehicle with a wireless communications link readily becomes an automatic vehicle. There is not a clear separation between autonomous and automatic, since the distinction hinges on how much processing is on-board. A dual mode vehicle can be operated either by the driver or by an on-board computer. The rich literature on vehicle-to-vehicle and vehicle-to-infrastructure communication is outside the scope of this paper. The IEEE Intelligent Transportation Systems Society, Vehicular Technology Society and Robotics and Automation Society address the technical issues.

This paper focuses on land vehicles that are capable of autonomous behavior but usually follow high level instructions. This paradigm is commonly used in commercial aviation where take-offs, landings, and mid-course navigation may be done under auto-pilot with directions from air traffic controllers. The aircraft pilot must exercise constant vigilance.

This paper addresses two possible implementations of land vehicle autonomy, concentrating on the first:

1. Autonomy only on a guideway reserved for automatic vehicles.
2. Full autonomy on normal city streets.

Method 2 may require occasional driver intervention. Quickly obtaining the attention of a distracted driver is problematic, especially if the sensors are not aware of a potentially dangerous situation. By contrast, method 1 would allow no driver control between vehicle entry into an automated lane and exit from that lane; the driver could request exit from the lane at the next opportunity.

An automated system does not assume centralized control; most of the intelligence could be on-board. Vehicle cooperation might emerge as a property of vehicle communication [2]. Most supervisory control could be distributed and scalable.

Single mode automated land transportation is in use worldwide. Autonomous commuter trains have been in operation since 1983. More than 130 rail-based automatic people mover systems are in service with dozens of others scheduled for implementation in the next few years [3]. Automation technology can be expected to be extended to buses, trucks, cars and light vehicles. We can expect to see improvements in driver assistance systems for smart cruise control, parking, navigation, bus and truck docking, lane following and accident avoidance. Instrumentation improvements to both infrastructure and vehicles will increase the intelligence of transportation.

It is impossible to know when or whether autonomous land vehicles will be widely deployed. Today's technology makes these vehicles feasible [4]. The biggest barriers to their implementation are non-technical and include liability, traffic laws, political will, finances, long lead times for transportation projects and popular mistrust. If the potential benefits of driverless transportation were widely appreciated and strong popular support emerged, steps could be taken to reduce the non-technical barriers.

In a companion paper, I argue that an entirely new mode of urban transportation is possible, based on small ultra-light vehicles, which are neither car nor bus nor motorcycle [5]. The present paper explores the energy consequences of such a system. There are many other designs that would produce similar results. Energy savings is dependent on the shape of transportation automation. The greatest effects on energy reduction come when the infrastructure, vehicles and their operation form a system optimized for that purpose.

This paper demonstrates how automation could decrease energy consumption by an order of magnitude. It shows feasibility, but makes no implementation predictions. This is not a discussion of the car or transit system of the future. It is a vision of how technology could transform the future of urban transportation.

II. FEASIBILITY

A. *A Transport Revolution?*

Few people could foresee the effects of the Internet 30 years ago. Most transportation planners make no provision for autonomous vehicles; autonomy may have a similarly disruptive effect on 30-year transportation plans. The World Conference on Transportation Research Society (WCTRS) recently released a report on whether global transportation sustainability is possible by 2050 [6]. They did not consider the effects of autonomy. Google has driven autonomous cars over 140,000 miles in traffic with only occasional human control, and 1000 miles with no intervention [7]. Google has correctly foreseen trends in other areas, and it would be reasonable to assume that the company saw a good business case for investing in autonomous vehicles.

A transport revolution can be defined as a substantial change in a society's transport activity that occurs in less than 25 years [8]. Examples of previous revolutions include:

1. Britain's move to railways, starting in 1830.
2. Substantial reversal of automobile travel in the U.S. during Wold War II.
3. The change from ships to planes for transatlantic travel.
4. The introduction of high speed rail from 1960 to 1985.
5. The use of air freight starting in 1980.

Gilbert and Perl [8] argue that several factors favor a revolution away from petroleum-based transportation:

1. High oil prices.
2. Concern about urban pollution.
3. Concern about climate change.
4. Concern about sustainability.
5. Avoidance of international conflict over energy resources.

To this list can be added technological capabilities.

The European Commission notes “If we do not address this oil dependence, people’s ability to travel – and our economic security – could be severely impacted with dire consequences on inflation, trade balance and the overall competitiveness of the EU economy.” [9]. The commission has set the goal of a 50% reduction in urban conventionally fueled cars by 2030, and their elimination by 2050.

The Rocky Mountain Institute [10] finds that the United States can eliminate all oil, coal and nuclear energy by 2050. Such a transformation would require no new inventions, taxes, subsidies or federal laws. The estimated cost difference from business as usual is a savings of $5 trillion. Two keys to increasing automobile efficiency are reducing weight by replacing steel with lighter materials, and improving aerodynamics

If a disruptive transportation event does occur, it offers an opportunity to redesign how people move in the city. Autonomy can play a key role. Americans drive 5 trillion kilometers per year, of which 65% are urban [11]. The car does best on the open road. The urban vehicle of choice may bear little resemblance to today's automobile.

If the future vehicle is not classified as a car, it will coexist with cars. People have emotional attachment to cars and those who prefer to drive may continue to do so. People had emotional attachment to horses, but horses are rare in today's city. Rural trips might be most convenient by car, bus or train. For urban trips, some people may prefer a non-automobile if it is more convenient, faster, cheaper, safer and better for the environment.

If transportation automation is deployed haphazardly, the beneficial effects will be reduced. A unified system will not happen until a wide swath of the population becomes aware of the possibility, and demands it. As technologists, it is up to us to educate planners, politicians, industrialists and the general public about what could be. As autonomy becomes a real option, there may be a transition window of a few years offering a chance for shrinking the prevalent vehicle size and improving fuel efficiency.

B. *Next Generation Automobiles*

Cars could undergo radical changes [12]. Four major ideas are:

1. Use design principles based on electric-drive and wireless communications.
2. Develop an Internet of vehicles and infrastructure.
3. Integrate electric vehicles with smart electric grids.
4. Implement dynamic pricing for roads, parking and electricity.

BMW is using a carbon fibre body for its i3 electric vehicle. BMW sales and marketing chief Ian Robertson said "A carbon body structure is 50-60 per cent lighter than a conventional body, and batteries are heavy. So suddenly you have a good business case. The smaller battery pack required by a lighter car offsets the cost of the carbon fiber body." [13]. Volkswagen claims 0.9 l/100 km (261 mpg) for its composite XL1 concept car [14].

C. *Personal Rapid Transit*

The notion of Personal Rapid Transit (PRT) dates from the 1960s. It is defined as [15]

1. Fully automated vehicles capable of operation without human drivers.
2. Vehicles captive to a reserved guideway.
3. Small vehicles available for exclusive use by an individual or a small group, typically 1 to 6 passengers, traveling together by choice and available 24 hours a day.
4. Small guideways that can be located above ground, at ground level or underground.
5. Vehicles able to use all guideways and stations on a fully coupled PRT network.
6. Direct origin to destination service, without a necessity to transfer or stop at intervening stations.
7. Service available on demand rather than on fixed schedules.

A system with most of these characteristics, but using large vehicles has been operating at Morgantown, WV since 1972. [16]. A PRT system has been recently constructed at London's Heathrow airport; the problem of precise vehicle control with 0.5 second headway has been solved [17]. PRT systems are offered by several commercial companies, but there have been few sales to date. The low number of installations can be attributed to:

1. The need to construct new infrastructure; PRT proponents argue that the guideways would be light, requiring little space.
2. There is no good reason why the vehicles must be captive to the guideway. There has been considerable discussion of the merits of single or dual mode [18].

D. *Platooning of Autonomous Vehicles*

Pioneering work on automatic highway vehicles goes back to the 1970s [19]. More recently, the National Automated Highway System Consortium (NAHSC) has demonstrated a platoon of eight cars driving automatically with a 3 meter gap between vehicles [20]. These cars produced a smooth ride and maintained the distance within ±20 cm. Following distances can be tightly controlled, but too precise positional accuracy results in an unsmooth ride [21]. Autonomous heavy trucks have traveled in a platoon with a 10 m gap in Japan; a truck has demonstrated an autonomous merge between two others [22]. In Europe, platoons of eight instrumented highway vehicles are being studied; a driver operates the lead vehicle and the following vehicles operate autonomously. A hierarchical vehicle network is under development with very high capacity links to provide door-to-door transportation to anyone at any time [23].

E. *Convergence*

An autonomous road vehicle can be operated as a rail-less PRT. The reserved guideways can contain embedded sensors or targets. Another technique is visual line following, though correct operation under all lighting and weather conditions is a challenge. The "rail" could become 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. Paved guideways enable much faster switching times than steel rails. Fast switching time removes a constraint on the spacing between vehicles and thus increases system capacity.

On an automated system, all vehicles would operate on the main line at full design speed with no intersections. A freeway lane, separated from other vehicles, could become an automated vehicle guideway.

PRT is usually envisioned as a connector system within cities to supplement line haul transit systems. Automated highways are a possibility for longer distances. The highway behaves as a reserved guideway using enhanced vehicles that are similar to what we drive today. Automated highways and PRT could converge into an integrated transportation system. Dual mode automated vehicles would operate under driver control when off the reserved guideway; the vehicle is thus capable of operating on all existing paved infrastructure.

III. SAFETY

A. *Traffic Accidents*

We seldom consider the danger of automobiles, since they are so common in our lives. In the U.S. in 2009, 30,797 fatal crashes killed 33,808 people. Death claimed 17,640 drivers, 6,770 passengers, 4,462 motorcyclists, 4,092 pedestrians and 680 bicyclists [22]. This compares to 16,591 deaths from homicides [25]. The 2,217,000 traffic injuries cost an estimated \$230 billion in economic value alone [26].

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 [27]. For the 20th century, 667,701 American troops have died at war and 3,070,325 Americans have died on the roads [28,29].

Worldwide, an estimated 1.18 million people died from road traffic crashes in 2002 [30]; this accounts for 2.1% of all deaths and ranks as the eleventh leading cause of global deaths. Road crashes injure between 20 and 50 million people each year. Projections indicate that road traffic injuries could reach third place as a global burden of disease and injury by 2020 [30].

Alcohol was involved in 38% of U.S. fatal crashes, and 1.44 million arrests were made for driving under the influence of alcohol or narcotics [24,31]. 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 [32]. The result is 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.

A 1985 study showed human factors contributing wholly or in part to 93% of traffic accidents in the U.S. and Britain [33]. An automated vehicle system might eliminate the human factors, but replace them with new problems, such as multi-vehicle collisions of a platoon when a vehicle suffers a tire blowout or a system malfunction. An automated system will be safer than the current system; if it is not, it will never be allowed to operate. The transition from steel to composite vehicles may also contribute to improved safety.

B. *Autonomous Trains*

Rail safety exceeds road safety by more than an order of magnitude. Table 1 gives data for death rates from different travel modes [34]. Records show that autonomy increases train safety by an additional order of magnitude.

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 [35]. This system is organized in two lines, includes 60 stations, extends over 45 km, and carried 86 million passengers in 2007 [36]. It has a peak speed of 80 kph and its average speed is 32 kph. The system has been replicated elsewhere.

Vancouver, Canada 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 [37]. Table 2 shows that these autonomous train systems are considerably safer than Light Rail Transit (LRT) or Rapid Rail Transit (RRT) systems.

Thus autonomy has improved already safe train travel by an order of magnitude. It would be reasonable to expect that autonomy could have a similar or greater effect on more dangerous transportation modes.

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

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

IV. System Capacity

Automation allows safe reduction in following distances; there is no driver reaction time. A modern automobile contains up to 50 microcontrollers, which communicate over a hostless CAN (controller area network) bus. Such protocols are mandatory in all vehicles sold in the U.S. and Europe. An automated vehicle would likely use vehicle-to-vehicle communication, and have access to portions the CAN bus of the vehicle in front of it; it thus knows the lead vehicle's maneuvers before they start.

The automated lanes could be separated from manually driven vehicles, pedestrians and animals. Thus the unknowns facing automated vehicles would be reduced to debris, ice, snow, mechanical failures and extreme events such as fire or earthquakes. If there is little variation in vehicle size, snow could be avoided by enclosing the automated lanes in a tube. The automated system is designed so that main line traffic always moves at design speed; there is no stop and go. If the system saturates, no new vehicles will be admitted, but those on the automated lanes still travel at design speed.

Automated traffic travels in platoons [38]. Technical capabilities will determine the safe size of the platoons, spacing between platooned vehicles and between platoons. These parameters determine lane capacity. At the base level of single vehicle platoons separated by the standard stopping distance, automated lane capacity equals standard freeway capacity. Freeway capacity can increase by 3 to 8 times as platoon size grows [38]. There must be adequate stopping distance between platoons, and enough space to break transmission of shock waves from any deviation of platoon speed from design speed. If the rider activates an emergency brake, that action is transmitted to all platooned vehicles before it happens, though such action is strongly discouraged. The extreme case would be vehicles that mechanically couple to each other like train cars, shrinking intra-platoon vehicle spacing to zero. Road trains could run in platoons of 100 vehicles, with a new platoon passing a fixed point every 30 seconds. At this extreme, lane capacity could reach 14,000 vehicles per hour. Lane capacity as a function of following distances is shown in Table 3. The table is based on vehicles of 3 m (10 ft) length traveling at 50 kph (30 mph). The table is based on vehicles traveling single file. If the automated vehicles are narrow enough to travel side-by-side, the values in the table double.

Table 3. Effect of Following Distances on Lane Capacity

Vehicle to vehicle spacing (m)	Vehicle to vehicle spacing (sec)	Platoon size (vehicles)	Platoon to platoon spacing (m)	Platoon to platoon spacing (sec)	Lane capacity (vehicles/hr)
15	1.1	3	10	0.7	2,344
5	0.4	6	20	1.4	4,412
3	0.2	8	25	1.8	5,479
2	0.14	8	25	1.8	6,154
2	0.14	20	30	2.2	7,692
1	0.07	30	30	2.2	10,000
0	0	30	50	3.6	10,714
0	0	100	50	3.6	14,286

The platoon structure allocates a slot for every potential vehicle on the system. Normally, most of these slots are empty. A platoon is filled as new vehicles merge onto the rear. Vehicles can exit from any position in a platoon by moving laterally, and taking an exit lane, with the remaining vehicles closing the gap. Autonomous merging behavior has been demonstrated for heavy vehicles. Proper control of vehicles in a platoon requires knowledge not only of the actions of the vehicle in front, but also additional vehicles further ahead in the platoon [39].

Achieving the theoretical capacities depends on the ability of the exits to absorb large numbers of vehicles without saturating.

One implementation of a fully automated system is to keep vehicles on the main line always traveling 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.

System costs can be shifted to either the vehicles or the infrastructure. If the cost burden falls entirely on the vehicles, they must be smart enough to deal with unpredictable manually driven vehicles; it is unclear whether Artificial Intelligence will ever be robust enough for this challenge. Furthermore, manual interlopers in an automated lane would destroy the choreography of the automated vehicles. Sharing costs between vehicles and infrastructure appears to be the most effective approach.

If right-of-way can be obtained, standard methods of building a transportation lane at, below, or above grade could be followed; however it may be less expensive to repurpose an urban freeway lane. Consider a three lane freeway that is converted to two normal lanes and one automation-only lane. If more than 1/3 of freeway drivers switch to automation, then the freeway has gained capacity despite losing a lane. This is true even if the automated lane is used at a fraction of its capacity. Infrastructure costs for freeway conversion would be construction of physical barriers between automated and non-automated traffic, and the construction of dedicated entry and exit ramps for autonomous vehicles.

When an automated system based on conservative following distances is put into place, it can be expected that future advances in software and control systems will substantially increase highway capacity without the need for any physical construction. Thus freeways would become less congested when new software is released.

V. 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) [40].

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) [41].

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

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 automated design minimizes starts and stops; further energy reduction can come from mass. The model T Ford weighed 545 kg, and had a 15 kW engine [42]. In 2003, EPA reported that the average U.S. car weighed 1820 kg [43]; the average American male weighs 86 kg [44]. 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 an **SUV has almost no safety advantage over a motorcycle**. An autonomous vehicle system presents the opportunity to build a transportation system around motorcycle-sized three- or four-wheeled vehicles.

The other energy 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 [45]. Drag can be decreased by streamlining the vehicle, and minimizing frontal area. Drag could be further reduced by enclosing the guideway in a tube to eliminate headwinds; tailwinds could be induced from vehicle slipstreams or from wind-powered fans. However, vehicle speed is more critical. 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 reaching peak speeds of 100 kph may have an effective speed of less than 50 kph when stops at stations and passenger wait times are included. For example, Link Light Rail connects downtown Seattle to the airport on a 25 km line. Trains leave every 7.5 to 15 minutes, with a scheduled journey time of 38 minutes and 11 intermediate stops [46]. Average speed is thus 40 kph, or 35 kph when an average wait time of 5 minutes is included. Thus an automated vehicle traveling at a constant 50 kph is faster than the train.

The behavior of automobiles in cities is captured in Table 4, which summarizes typical conditions used to determine city fuel efficiency ratings [47]. Designing an honest 50 kph constant average speed without a peak 100 kph speed is not a reduction in performance.

Table 4. Characteristics of city driving cycles

	Average speed (kph)	Maximum speed (kph)	Time stopped or decelerating (%)
U.S.	31	91	43
Europe	33	119	25
Japan	24	70	52

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 tandem 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 attach a second vehicle to carry purchases.

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 5 gives the energy requirements per person of various vehicles [45].

Table 5: 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. Typical power required for a pod car to maintain speed is shown in Figure 2., which assumes level ground, no acceleration and a total mass of 200 kg. Fuel consumption is related to the power expended.

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, which achieved 0.075 l/100 km (3145 mpg) in a gasoline powered vehicle, apparently at speeds of 20 kph [48,49]. 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 streamlined three-wheel motorcycle driven on California freeways. The vehicle weighed 105 kg, and was powered by a 1900 W gasoline engine [50]. The mileage can be expected to improve at lower speed.

[Figure 1 is in PowerRequired.xls or AlternateFigure1forMac.glx]

Figure 1. Power dependency on speed.

An electric pod car has driven 100 km in one hour. Energy efficiency was 9.5 W hr/km or 0.11 l/100 km (2200 mpg) at freeway speed [51].

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 such as the Nissan Leaf may carry 300 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 provides about 50 km of range to an ordinary electric bicycle or motorcycle weighing 200 kg with rider [52]. An aerodynamic pod car would do much better, since the drag coefficient in equation (2) would be 3 to 6 times less. 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 [53]. Total vehicle kilometers were just under 5 trillion, with 65% classified as urban and 35% as rural [11]. 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 [54]. 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 an automated urban 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. The reduction is 16% of U.S. oil consumption and 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, equivalent to 12 trains of 100 coal cars.

VI. TRANSITION

A. Public Transportation

Driverless taxis solve a dilemma of public transportation whose capacity may be strained at peak times, but is forced to operate near-empty coaches at other times. A system of self-driving vehicles adapts to the load. In the U.S., busses get worse mileage per person than cars because of low ridership [47].

An automated system could incorporate both public and private transportation; this is the key that makes transition to an automated system practical. When a city decides to install an autonomous public transportation system, the city would set up the lanes and buy thousands of public single mode vehicles, following the paradigm for installing a light rail system. The public vehicles would be boarded only at stations adjacent to the entry ramps for the restricted lanes; disembarkation would be similarly limited.

The system could be expanded to accommodate dual mode vehicles. A private dual mode 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 private vehicle is then issued an encrypted code which allows it to operate on the system under computer control. After passing the gate, all manual control of the vehicle becomes impossible. After the vehicle exits from the system, and comes to a stop, manual control is restored. Accomplishing this feat implies that the dual mode vehicle must be driven by wire, rather than via mechanical linkages. Entry to automated lanes could be restricted either by installing physical barriers or by equipping automatic vehicles with the ability to ticket any vehicle that does not properly respond to a vehicle-to-vehicle communication.

Pod car implementation could be in stages:

1. A metropolitan area installs reserved guideways, stations and public single mode ultra-light vehicles as for light rail.
2. The city introduces public dual mode vehicles which are similar to a bike share or car share program [55].
3. Inspection stations are established to verify private dual mode vehicles; such vehicles become available for lease or purchase.
4. Broad acceptance of narrow ultra-light urban vehicles leads to changes in city street configurations.
5. Driver-less operation of ultra-light vehicles on city streets becomes technically feasible, safe and legal.

Dual mode automated vehicles fill the first and last mile gaps in public transit. The distance between the trip origin and the closest station ceases to be a problem; the same dual mode vehicle makes the entire journey. The vehicle 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; the city can collect tolls from private vehicles.

In our current transportation system, a private car is much more convenient than a public bus. In an automated 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. If full autonomy on city streets becomes possible, a public vehicle could 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.

B. Liability

Liability issues could slow or prevent 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 [56]. A system that has no dependency on the driver may produce less legal exposure for manufactures. Nonetheless, liability concerns are a major barrier.

The non-technical barriers may prevent the United States from adopting dual mode road vehicles. Europe has stronger motivation to adopt automated transportation systems due to greater awareness of climate change. Most of the barriers do not apply in China; thus that nation could be the first to deploy the technology. China is the world's leading producer and consumer of electric vehicles, most of which have two wheels [57]. China is committed to electric vehicles, and the system envisioned in this paper would be a good fit to China, where there are 100 cities of a million people or more. It is possible that automated vehicles would be accepted elsewhere after they are proven in China.

If liability were not a consideration, the people mover system could be designed and manufactured in the United States and exported to China. Legal barriers to acceptance of autonomous vehicles in the U.S. could make trade go the other way, with the effect of more green jobs going to China.

VII. Other Effects

In addition to huge improvements in traffic safety, congestion and energy use, the transition to autonomous vehicles would have numerous other effects. Total computer control of personal transportation topples many barriers.

A. Greater Access to Transportation

Some disabilities, such as blindness, preclude driving. A fully autonomous vehicle only requires the rider to be able to select her destination, thus opening 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, threatening injury or death to the driver or others. Individuals must either be capable of recognizing the situation and surrendering their driver's license, or doctors or relatives must force this outcome. This is a stressful time for everyone involved, since loss of mobility isolates elders. With autonomous vehicles, there is no need for elders to lose mobility. Retirement communities are prime candidates for small scale autonomous vehicle systems.

At the other end of the age spectrum, autonomous vehicles grant greater mobility to children. School buses would become obsolete as parents or teachers strap children into automated vehicles, and set a non-overridable destination. Parents would 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. The Urban Landscape

A typical U.S. suburban business district devotes an enormous amount of land to parking, causing 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 [58]. This in turn leads to declining populations of salmon, orca whales and other marine life.

Parking lots accommodate peak demand, and during a 24 hour period are rarely full. An autonomous system requires fewer vehicles and less parking. A public vehicle can deliver a rider to her destination, then drive itself to the next person requesting transportation. A private vehicle can drop the rider at his destination, and then drive itself several kilometers to park. If full autonomy on city streets becomes possible, deliveries could be made without a driver, impacting messenger service, restaurant food delivery and other service sectors.

C. Health

Estimates of the cost of air pollution vary widely. A reasonable estimate of the annual cost of air pollution in U.S. metropolitan areas is $55 billion [59]. Tailpipe emissions could be eliminated.

The pod car is small enough that a major portion of its power could be supplied by the rider. This could take the form of a hybrid electric / human powered vehicle model. Direct human power would not be practical under automation, since the vehicle must maintain precise speeds; the rider's energy can instead be used to charge a battery. The health benefits of cycling have been found to outweigh the risks [60]; the pod car is expected to be safer than a bicycle because the rider is encased in a composite shell. The standard model pod car would be powered by an electric motor only.

Automobiles externalize costs that are paid for by general taxation: accidents, pollution, congestion delays, climate change and noise. The total annual value of externalized costs is estimated at $820 billion in the U.S. [61]. This does not include the costs of roads, parking, policing or national security.

VIII. Conclusion

I make no predictions whether any of this will come to pass; based on the record of human stupidity, it is more likely that we will trash our environment until it kills us. If instead, we choose to survive and thrive, we have options.

An automated urban traffic system based on vehicles weighing less than the riders could be powered by a swappable 10 kg battery, reducing transportation energy requirements. Automation 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 may reduce sprawl and impervious surfaces since fewer freeway lanes and parking lots would be required. 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 July 20, 1969, the dream was reality. A similar effort could put people mover systems in place in a similar time frame. The annual cost of the Apollo program was $18 billion in 21st century dollars [62]. The payoffs from developing people mover systems could exceed those from the space program.

Transportation experts are notoriously inaccurate when predicting the costs of known technologies. No one knows what an automated system would cost; predictions vary wildly. Ultra Fairwood has recently signed a contract for a vehicle and guideway autonomous system in Amritsar, India on a build, own, operate, transfer basis [63]. If they are successful in building a system with private financing and making a profit from fares, the consequences could be enormous.

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