The Autonomous Tricycle

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ABSTRACT

Autonomous ultra-light vehicles offer enormous potential for improvements in transportation safety, economy, energy consumption, and congestion. In this context, “ultra-light” means a vehicle that weighs less than its riders. A bicycle or motorcycle may meet this criterion; to facilitate computerized vehicle control, a third wheel is added. The present paper discusses how such a system would operate and paths to implementation. A system is proposed where all vehicles are under computer control and always travel at design speed. Setting the design speed at 50 kph would often reduce the trip time of today's 100 kph capable vehicles. The system is able to maintain design speed at saturation and does not congest. The result is a new transportation mode that blurs the distinction between public and private transportation. Safety can improve by an order of magnitude. Energy efficiency can be hundreds of mpgE. The main technical challenges are systems and software.

1. INTRODUCTION

In the Netherlands, bicycles are used for 27% of urban trips (1). Few other countries can match the Dutch performance. Several Asian countries have had comparable bicycling rates in the past, but as the population becomes more affluent, the trend is from bicycles to cars. In the United States, 88% of commuters use a car and fewer than 1.2% use a car or motorcycle (2). The present paper explores how the bicycle could be transformed into a new transportation mode offering the convenience of a car, the safety of a train, the compactness of a motorcycle and the public transportation capabilities of a bus or taxi.

Various factors inhibiting bicycle use have been identified among people who bicycle to work frequently or occasionally (3). These include:

- Weather: Rain, temperature and wind
- Distance and the need to work at multiple locations
- Need to wear business attire and desire to avoid perspiration

Pleasant weather has a positive effect on bicycle usage. Women cyclists are often concerned about (4)

- Safety
- Being able to carry daily items
- Need to fix hair on arrival

The health advantages of cycling outweigh the risks (5). However, one might conjecture that people who never commute by bicycle perceive cycling as a risky activity.

Various programs have been undertaken to encourage cycling and reduce traffic congestion. Low-cost bicycle rental systems have been introduced in Copenhagen (in 1995), Helsinki (2000), Oslo (2002), Stockholm (2006), Barcelona, (2007), Paris (2007), and Brussels (2009). There are at least 100 bike-sharing programs operating in 125 cities worldwide (6).

Adding an enclosure to a bicycle makes it a human powered vehicle (HPV) or velomobile. The fairing may provide protection from rain, snow, cold and heat. The most energy efficient vehicles are human powered. If the fairing is light weight, has a low drag coefficient and minimal frontal area, the result can be a vehicle three times as efficient as a bicycle. It is capable of higher speeds with the same power. The world HPV speed record is 133 kph (82.8 mph), set by a vehicle similar to that in Figure 1 (7). This is the time to traverse a 200 m trap from a flying start without benefit from hills or tail wind. The 1 hour standing start record is 90 km (56 miles).

FIGURE 1 High speed HPV.

An athletic human can produce short burst power of 1 to 2 kW or sustained power of 300 to 500 W (8). An ordinary healthy individual can produce 100 W all day. This is the power range that drives bicycles and HPVs. The power can come from any source: human, electric motor, gasoline engine or a hybrid of these. This paper proposes building a transportation system around pod cars. These are vehicles similar to an HPV, but with three wheels, powered by an electric motor, designed for comfort, ease of entry and capable of carrying the amount of goods that a person might normally carry.

Using an electric motor removes the cycling disincentives from wearing business attire or concern for hair. In the US, a vehicle with an electric helper motor of 750 W or less and a top motor speed of 20 mph (32 kph) is treated as a bicycle (9). Such a motor puts out more power than an athlete. With the right aerodynamics, 750 W is sufficient to cover 80 km (50 miles) on the level in an hour. A 36 volt motor needs 14 amps to fully utilize a 500 W motor. A 1.4 Amp-hour battery capable of providing this power for 1 hour would weigh 4 kg (9 lb) in lithium or 13 kg (28 lb) in sealed lead-acid.

In practice, battery characteristics require a bit more power to achieve this range. Electrathon is a contest that tests the distance that a pod car can travel in one hour using a single charge from stock lead-acid batteries limited to 73 lb (33 kg). The record is 100 km (62 mi) in one hour. Energy usage was 0.95 kW or 0.11 l/100 km (2200 mpg) equivalent at freeway speed (10).

The per person power required for various vehicles at 50 kph is shown in Table 1 (8). The HPV figure is for a vehicle designed for commuting; a vehicle designed for racing needs less energy. Few humans are capable of riding a bicycle 50 km in an hour. The automotive figure is based on a car getting 38 mpg (6.2 l/100 km).

TABLE 1 Energy Consumption per Person at 50 kph (30 mph)

Vehicle Type	Energy (kW / person)
HPV or pod car	0.64
Bicycle	1.74
Train and riders	6.51
Car and 5 riders	6.98
Car and driver	31.3

Since transit ridership is low in the US, passenger cars achieve better or comparable per person mileage than transit, as shown in Table 2 (11). The car in Table 2 is assumed to get only 21 mpg. Running near-empty buses is not an energy efficient solution. There is a need to match transit capacity to the actual demand.

TABLE 2 Energy Efficiency of Transportation Modes

Transport Mode	Average Passengers per Vehicle	Efficiency per Passenger	
Van pool	6.1	1,322 BTU/mi	(87 MPGe)
Motorcycles	1.2	1,855 BTU/mi	(62 MPGe)
Rail (Commuter)	31.3	2,996 BTU/mi	(38 MPGe)
Cars	1.57	3,512 BTU/mi	(33 MPGe)
Personal Trucks	1.72	3,944 BTU/mi	(29 MPGe)
Buses (Transit)	8.8	4,235 BTU/mi	(27 MPGe)

2. AUTONOMOUS VEHICLES

An autonomous commuter train has operated in Lille, France since 1983, including 60 stations and covering over 45 km (12). Other automatic people movers are in place in dozens of locations worldwide. Thus automated guideway transit is a proven technology. With today's technology, the rail is no longer needed. It is feasible to run buses autonomously on a reserved guideway. Automated driver assistance for bus docking has been demonstrated. Commercial driver assistance systems provide lane following and collision avoidance.

Google has driven autonomous cars 140,000 miles in city traffic with only occasional driver intervention and as far as 1000 miles with no driver intervention (13). This is a remarkable achievement, but this paper focuses on a technically easier situation: by providing a reserved lane for autonomous vehicles that is physically barricaded from non-autonomous traffic, there is reduced need to deal with unexpected vehicle behavior. Rather than trying to retrofit existing passenger vehicles, autonomy can be used as a wedge to replace the existing urban fleet with vehicles better matched to short trips. Most families will retain a conventional car for longer trips.

3. PROPOSED SYSTEM

The proposed system would have some of the characteristics of a Personal Rapid Transit (PRT) system: small public autonomous vehicles that run on demand 24/7. There are no schedules and the vehicle travels from the origin to destination on the most direct route with no stops. The vehicles travel on a reserved guideway (14).

The proposed system would differ from a PRT by offering dual mode vehicles and requiring that all vehicles always travel at design speed on the main line. PRT vehicles are often designed for four to six riders; the ultralight system may be built on vehicles designed for one or two riders. PRT is often proposed as a short haul feeder system servicing line haul routes. By contrast, the proposed system could replace most buses. The proposed system would have greater capacity than a freeway lane and approach the capacity of light rail.

The proposed system would be built around pod cars. These resemble velomobiles in minimal frontal area, low drag coefficient and low weight. A single person pod car would be less than a meter wide, about 1.4 meters high and about 3 meters long. A two person model would be longer. They would differ from velomobiles in providing easier entry and exit, improved suspension and ventilation. A pod car is powered by an electric motor. It may or may not be a hybrid with supplemental human power supplied by pedaling.

Pod cars are modular. Several can be linked to form a larger vehicle when needed. The linkage may or may not include physical coupling. Pod cars are autonomous. When operating as a larger vehicle, the lead pod is designated master and the others slaves. The slave cars are forced to travel with the master with no changes possible by riders in the slaved pods. Pod cars will contain communication devices similar to smart phones, enabling all occupants of a combined vehicle to converse. A person may take a single pod car to the store and return with extra slave pods to take purchases home.

Pod cars run autonomously on dedicated roadways or manually on city streets. Because the vehicles are dual mode, the grid of automated pathways does not need to be as dense as a good public transportation network.

Dual mode eliminates the gaps at the start and end of the automated ride. The pod car knows its destination and calculates the best route. A pod car is capable of running autonomously, meaning that the vehicle can follow the path and make its own decisions about when to turn or stop. More often the pod car will run automatically, where it takes high level commands from a traffic control computer. The high level commands will direct the car's timing for entering the automated system.

A pod car network is analogous to a commuter rail network with dedicated tracks, stations and vehicles designed to operate on the system. The simplest pod car network would use single mode public vehicles that never leave the network of automated paths. A rider would select her destination and pay the fare at a station. The station layout is shown in Figure 2. The rider goes to one of several parallel bays to which available pod cars drive themselves. She boards the car, inserting her receipt to notify the pod car of the destination. A more sophisticated pod car system would use dual mode vehicles that can be manually operated off the automated network.

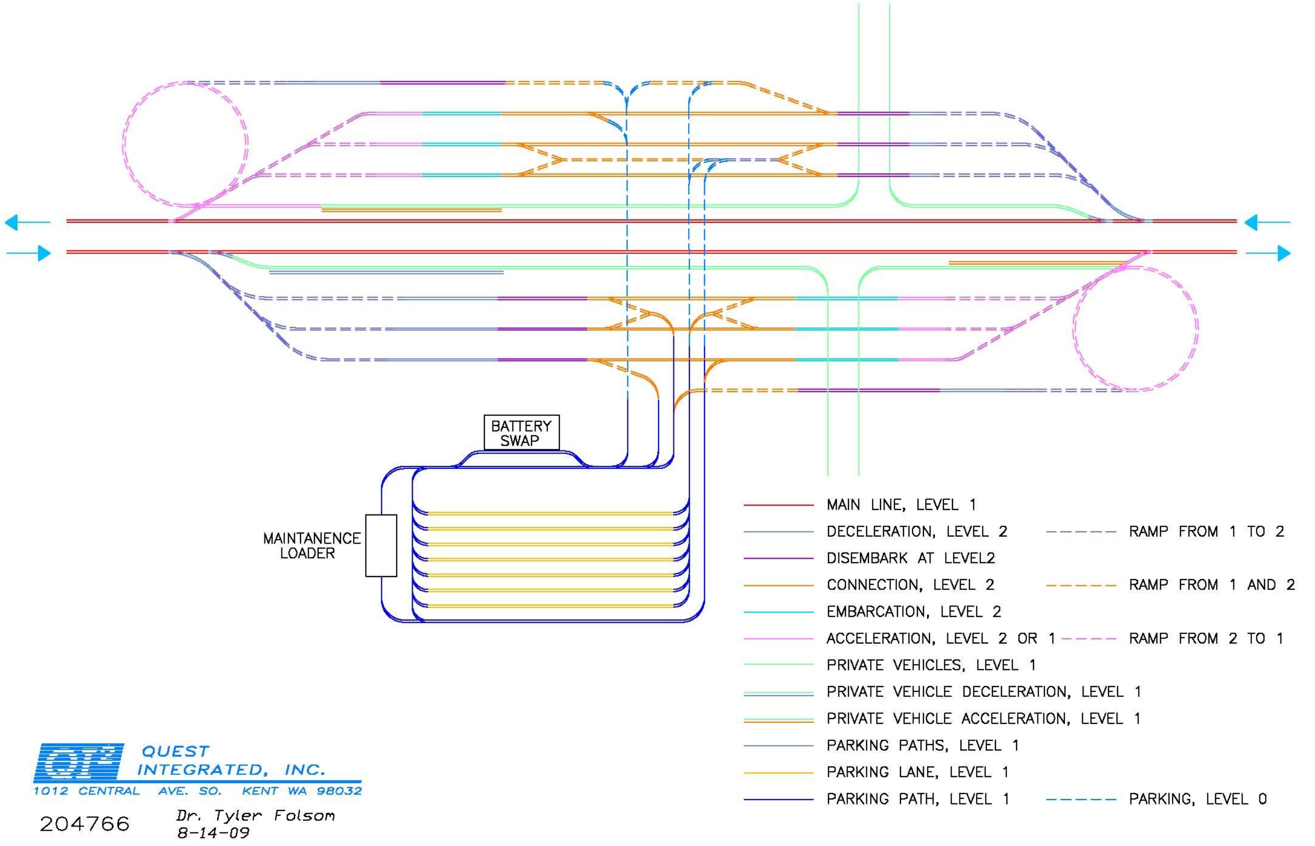

FIGURE 2 Station layout.

There is a traffic control computer (TCC) at each station. The TCC is responsible for the motion of all vehicles in the station vicinity. It directs vehicles exiting the main line into the appropriate bay. Once a vehicle discharges its passenger, it may proceed to pick up the next passenger, go to a refueling station, or be directed to wait in a pod car parking area. The pod car knows if it needs refueling and if so communicates that to the TCC. Otherwise, the TCC directs the car to either a loading bay or parking area.

Once the pod cars are ready to return to the main line, they form a queue at the entry ramp. The TCC determines the exact timing to merge into traffic. The TCC is aware of the location of every vehicle in its sector. It thus knows exactly when and where the new vehicles can merge onto the tail of a passing platoon without disturbing the motion of any vehicles on the main line. The TCC gives permission to an appropriate number of the queued vehicles to merge into a platoon at a precise split-second. In case of an unforeseen occurrence in which the merge space is not available, the merge ramp has an escape ramp that allows the vehicle to return to the station and try again. If the failure to merge was due to vehicle acceleration limits or other malfunction, the passenger is brought to another vehicle and the defective one routed to a maintenance facility. There will be specialized tow vehicles at each station capable of bringing defective vehicles to a central maintenance area. The tow vehicles are autonomous and satisfy the height and width limitations of the pod car system.

Any vehicle can exit a platoon from any position. As the main line approaches a station, an exit lane appears. Exiting vehicles detach themselves from the platoon and move into the exit lane. The remaining vehicles then close up the gaps in the platoon.

System computer control is distributed and scalable. Much of the computation is done in the vehicles themselves. There is a TCC controlling the traffic into, at and from each station. The TCC knows the positions, speeds and accelerations of all lead and tail platoon vehicles in its sector. The entire grid is divided into sectors, with each sector containing a station and TCC. When vehicles leave a sector, the TCC for that sector hands off information to the next TCC. Main line traffic always moves at design speed. If the system saturates, the TCC will not allow any new vehicles to enter. Every interchange has its TCC to direct the timing of vehicles that need to change from one line to another. If there is no space for such a merge, the vehicles are temporarily diverted to a holding area until they can merge at full speed.

There is a central system control computer that coordinates the actions of the TCCs, but under normal circumstances there is little for the central computer to do. If too many vehicles accumulate in a station, the central computer will direct the station TCC to send empty vehicles to where they are needed. If any portion of the system is shut due to maintenance or accident, the central computer will notify all TCCs.

When there is an accident on a link between stations, the central computer will notify all TCCs. Each TCC will then relay this information to all vehicles in its sector, which will replan their routes if necessary. The TCC downstream from the blocked link will refuse to let any new vehicles enter the blocked link. Vehicles entering the blocked station will be diverted to parking, with their riders given the choice to use other transportation modes and presented with an estimate of journey times. Each station must be large enough to accommodate maximum traffic flow with all vehicles destined for that station.

The TCC will direct all vehicles behind an accident to back up to the station and wait there. Meanwhile, emergency pod vehicles will be sent from the station upstream of the accident. They will wait until all vehicles in front of the accident have reached their station, leaving a clear path to the accident. Emergency vehicles may travel opposite to the normal flow of traffic.

The public pod car system is wheelchair accessible. A handicapped person may need to be transferred from the wheelchair to the vehicle, with the wheelchair transported in a slave vehicle. Each station will have attendants to provide assistance. The experience with the Lille autonomous train showed that unmanned stations can encourage crime. Thus Lille has hired station attendants whose job is to provide help to the public. Around-the-clock station attendants should be budgeted into the operating costs of the proposed system.

An urban area would put a single mode pod car network into place the same way that a light rail system would be built. The city would build the reserved lanes and purchase vehicles for public use. Once the system is in place, people may want to buy or lease private vehicles to use under automatic control. Such vehicles would be dual mode. On the reserved guideway they would operate identically to the public vehicles. Instead of the rider disembarking the vehicle at the destination station, a private vehicle would be directed to come to a stop in a holding area where the TCC relinquishes control. The driver would then set the vehicle for manual control and drive it normally on city streets.

Any dual mode vehicle would need to pass a test demonstrating that it is capable of operating on the automated system. On passing the test, the vehicle is issued electronic credentials. Each station would have a transition area for entering dual mode vehicles. When the vehicle's credentials are accepted, the driver loses all ability to control the vehicle. The vehicle follows the TCC's directions and passes a physical gate to enter the system. It then operates identically to the public vehicles. A toll may be charged for use of the automated system.

If the vehicle's credentials are not acceptable, it is not allowed onto the automated highway. It is possible that the user may have modified his vehicle after passing the test and it no longer conforms to requirements. Vehicle operations are controlled by firmware that is not readily user modifiable. An integrated circuit for security is part of the control system for each pod car. This chip will verify that the firmware is permissible and make hacking almost impossible. If the vehicle has been modified mechanically and is incapable of accelerating as required on the entry ramp, it is instead routed to the escape ramp, credentials are revoked and the vehicle rejected from the system. Any other detectable user tampering is treated the same way.

Pod cars are electric vehicles. Energy requirements are reduced by the vehicle light weight, aerodynamics and operation at a constant speed of 50 kph instead of stop and go with a 100 kph maximum. A disadvantage of electric automobiles is that achieving a range of 100 to 300 km requires batteries that increase vehicle weight beyond that of a comparable gasoline car.

The average US person trip length is 9.7 miles (15.6 km), with an average of 3.8 daily trips per person (15). Trip purposes and lengths are given in Table 3. Only two categories have average lengths of 20 miles or more and these account for only 15% of the total personal miles traveled. In all other categories, the average trip length is under 12 miles. The average commute speed in a metropolitan area is 28 mph (45 kph). These trip lengths are solidly within the range that the proposed system is designed to handle.

TABLE 3 Lengths of U.S. Trips with Percentage of Total Personal Miles Traveled

Trip Purpose	PMT	Average trip length	
	(%)	(miles)	(km)
Social and Recreational	30%	10.7	17.3
To/From Work	19%	11.8	19
Other Family/Personal errands	16%	7	11.3
Shopping	14%	6.5	10.5
Other	9%	51.5	83.1
Work related business	6%	20	32.3
School / Church	6%	6.3	10.2

Pod cars are designed to be urban people movers. They are not suitable for long distance travel or freight. When the range of a pod car is set to be 30 miles (48 km), it can be powered by a 1 kW engine and a 35 lb (16 kg) lead-acid battery. Using lithium batteries would require 1/3 this weight. With a small battery, refueling can easily be done by battery swap. Each vehicle can calculate its range and route itself to a refueling station as needed. The number of acceptable battery models would be severely restricted.

Pod cars can be built for any design speed and range. When speed and range increase, motor and battery size will also. Battery size should not increase beyond what is easily swappable.

4. SYSTEM CAPACITY

It is possible to operate a pod car system without taking advantage of the reduction in following distances allowed by automation. Such an automated lane would have the same capacity as today's freeway lanes. Half-wide vehicles allow a single freeway lane to be converted to two pod car lanes, doubling capacity. Since the pod cars have a low maximum height and are light weight, it would be feasible to stack lanes, producing four lanes where there had been one. Stacked lanes would require the expense of new construction.

Automation allows safe reduction in following distances. There is no driver reaction time. Each vehicle has access to the CAN bus of the vehicle in front of it and knows that vehicle's maneuvers before they start. The automated lanes are barricaded from manually driven vehicles, pedestrians and animals. This reduces the unknowns that automated vehicles must deal with to debris, ice, snow, mechanical failures and extreme events such as fire or earthquakes. Ice and snow could be avoided by enclosing the automated lanes in a tube. The system is designed so that traffic on the main line 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.

Main line pod car traffic travels in platoons. Technical capabilities will determine the safe size of the platoons, spacing between platooned vehicles and between platoons. These parameters determine lane capacity. At the lowest level of single vehicle platoons separated by the standard stopping distance, lane capacity is identical to freeway capacity. It has been shown that freeway capacity can increase by 3 to 8 times as platoon size grows (16). 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. Every vehicle in the platoon has access to the CAN bus of the vehicle in front of it and thus knows its motions before they begin. If the rider activates an emergency brake, that action is transmitted to all platooned vehicles before it happens. Such action is strongly discouraged. In the extreme case, it may be possible to shrink intra-platoon vehicle spacing to zero, perhaps with the use of mechanical coupling. This could lead to 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 4. The table is based on vehicles of 3 m (10 ft) length traveling at 50 kph (30 mph).

TABLE 4 Effect of Following Distances on Lane Capacity

Vehicle to vehicle spacing		Platoon size	Platoon to platoon spacing		Lane capacity
(m)	(sec)	(vehicles)	(m)	(sec)	(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 from the front and new vehicles merge onto the rear of a platoon. 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 (17).

A goal is to require minimal infrastructure construction for the conversion to pod cars. If right-of-way can be obtained, standard methods of building a transportation lane at, below or above grade could be followed. It would be less expensive to repurpose an urban freeway lane. A freeway lane can become two pod car lanes, each of which has double the capacity of the freeway lane when operated with a readily achievable vehicle spacing. If more than the number of drivers that formerly used the freeway lane switch to pod cars, then the freeway has gained capacity despite losing an automotive lane. Under this scenario, the only infrastructure costs would be construction of physical barriers between automated and non-automated traffic and the construction of pod car stations.

When a pod car 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 capacity without the need for any physical construction.

5. SYSTEM COSTS AND BENEFITS

A network of ultra-light autonomous pod cars offers:

- Order of magnitude improvements in traffic safety (18). When the computer controls all vehicles, accidents become rare and a motorcycle is almost as safe as an SUV.
- An end to drunk driving.
- Increased urban highway capacity.
- An end to congestion.
- A major reduction in urban gasoline consumption.
- Corresponding reductions in diseases caused by air pollution.
- Reductions in green house gases.
- Day and night transit availability with no waits and shorter trip times.
- A complete private vehicle inspection system for compliance with automation, safety, emissions, size and weight restrictions.
- An method of totally enforcing these requirements on automated highways.
- No driver moving vehicle violations when under computer control.
- Reduced width of lanes and right of way.

Surprisingly, there are few technical barriers to realizing these benefits in the near term. Most of the obstacles are legal or political. The main technical requirement is development and certification of systems and software. Operational software must be certified to avionics standards and tested to the point that liability concerns do not prevent implementation. The litigation climate in the United States may prevent initial system implementation. The concept may need to be proven in Asia or Europe before it is acceptable in the US.

A pod car system would cost less than existing public transportation systems. Typical bus vehicle costs range from $245,000 for a suburban bus to $811,000 for a 55 ft articulated bus (19). The estimated price for a pod car would be similar to that of a velomobile with an additional $2500 for an electric motor system and $2000 to $3000 in electronics, sensors and actuators. Typical velomobile prices are $10,000 to $14,000 (20). This would indicate a pod car price of $14,500 to $19,500. The price would likely drop considerably in large quantities, since only a few hundred velomobiles have been manufactured. An estimated initial pod car price would be about $15,000, which means that 50 of them would cost less than a large bus. Table 1 shows that the energy required for one passenger car could power 49 pod cars. The energy needs of a bus are several times those of a car. With mass production, the price of an autonomous pod car could drop below $10,000.

Pod cars are designed to use existing infrastructure. Where new construction is needed, costs would be similar to other transportation modes. Pod car operating costs would be lower for fuel but perhaps higher for maintenance. No drivers would be needed, but this is offset by the need for station attendants.

Seattle is in the process of constructing a light rail system. The initial 15.6 mile section paralleling I-5 from downtown Seattle south to the airport opened in 2009. An additional 3.15 mile line from downtown north to the University of Washington is scheduled for completion in 2016 (21). The capital plan for lifetime cost of the Link Light Rail System is $4,384,230,000 (22). The spur to the University of Washington costs $1.9 billion (23).

A reason for these high costs is the hilliness of Seattle and the inability of rail vehicles to climb steep grades. Thus deep tunnel excavation is required. Pod cars would not have this expense since there are several mechanisms by which they could climb hills:

- Equip the vehicles with larger motors and batteries.
- Use a slower hill climbing speed, but add extra uphill lanes so that every section of the network has the same throughput.

- The pod cars could clamp onto a cable to be towed uphill.
- Rotterdam has a bicycle only tunnel under the Maas River. It has escalators at either end. Similar escalators for pod cars could be installed.

The Seattle monorail is the only public transportation system in the US to have been built and operated at a profit. The intent of a pod car system is to lower the costs of public transportation so that it becomes profitable and dependency on government subsidies is no more than for the automobile.

6. IMPLEMENTATION PATHS

There is movement in Europe toward a system with many of the proposed characteristics (24). Several companies offer PRT systems and several communities have adapted them or are considering doing so (25). The Transportation Research Board has a Vehicle Highway Automation Committee. A pod car system can be implemented by a municipality and does not require adoption by an entire nation. There is an educational effort to build a low cost open source prototype autonomous vehicle to spread awareness of the possibilities (26).

Present trends in transportation can be redirected to implement the pod car system. Bus Rapid Transit (BRT) is increasingly using driver assistance technology on reserved busways. Electronic systems are able to dock the bus at the station without driver assistance. Other driver assistance systems help keep the vehicle in lane and prevent collisions. These electronics are expensive, but the price can fall by orders of magnitude if a mass market develops.

The future BRT may evolve to semi-automated vehicles in which the driver is only needed in case of emergency. Instead of running a large bus in non-peak times, it would make sense to operate a van as the lead vehicle in a road train. The following vehicles would be ultra-light autonomous pod cars. The main vehicle could be operated as an express that stops only at the origin and terminus of the line. People with an origin or destination at an intermediate station would travel in pod cars that join the platoon as described above. After this system has operated for a number of years, it may be found that the driver is not needed in the lead vehicle. The result is the described single-mode pod car system. Such a system can evolve into the dual-mode system with the construction of entry and exit ramps for private vehicles and a vehicle inspection system.

Another implementation path would be to convert freeway HOV lanes to autonomous use. This would require barricading the HOV lane from non-autonomous vehicles and building separate entry and exit ramps to the automated lane.

Pod car implementation would be in stages.

1. A metropolitan area installs reserved guideways, stations and public single mode ultra-light vehicles as for commuter rail.
2. The city introduces public dual mode vehicles which are similar to a bike share or zip car program.
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.

7. CONCLUSION

The technology is at hand to build an automated public transportation system based on highly efficient ultra-light vehicles. Such a system would offer order of magnitude improvements in the rate of traffic accidents and energy consumption. There are feasible scenarios for introducing such a system though retrofits to existing infrastructure at reasonable costs. A single-mode pod car public transportation system should be designed to be expandable to service dual-mode private vehicles. When operated for dual-mode, the pod car system blurs the distinctions between private and public transportation.

The area most in need of further research is safe reduction of following distances for automated vehicles. Most of the benefits of the pod car system can be obtained using present standards for vehicle spacing. System capacity is strongly dependent on vehicle spacing. Developing software algorithms or mechanical coupling systems to shrink spacing distances to near zero can give a freeway lane the capacity of light rail.

In the 1930s, films such as *Just Imagine*, *Metropolis* and *Things to Come* envisioned the city of the future as containing gleaming towers connected by people movers (27). There was even a prediction of a trip to the moon by 2000. In many areas of technology we have advanced far beyond what people could dream of 75 years ago. We have reached the moon, but fallen far short of building efficient people movers.

In 2005 dollars, the Apollo moon mission cost about $18B per year or $165B over nine years (28). The annual cost of US traffic accidents is estimated at $230B per year (29) with automotive air pollution costing an additional $53B (30). The pod car system requires far less new technology that the moon shot and offers greater payoffs.

The economic savings from reduced accidents, air pollution and fuel consumption may exceed the development, capital and operating costs of installing the system. A goal of the pod car system is to reduce costs to the point that public transportation can generate a profit. System revenue from fares and tolls may offset development and installation costs. A pod car system could be a good investment for a national government or private company.

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