Improved Bus Service on Ten Times Less Energy

Tyler C. Folsom(✉)

University of Washington, Bothell, WA, USA
tfolsom@uw.edu

Abstract. We have designed the MilliPod™, a platoon of electric, fully automated two-person microvehicles following a professionally operated lead vehicle. The MilliPod picks up passengers without stopping and uses an order of magnitude less energy than the transit buses it replaces. To reduce congestion, the pods physically couple to each other, but are all individually powered and steered creating an agile all-wheel drive vehicle.

The MilliPod is designed to move people in the city with minimal energy. It is expected to cost less than a bus but provides faster trips A major technical contribution is a control system that will let the pods drive bumper-to-bumper smoothly.

The MilliPod achieves its efficiency by applying automated vehicle technology to microvehicles weighing less than the riders. It takes advantage of the high energy efficiency required for human-powered vehicles that can break highway speed limits. The passenger pods are fully automated, but are restricted to a limited operational driving domain, and depend on a professional operator to ensure safety. This level of automation can be done with today's technology.

Because of its high energy efficiency, each pod can be powered by a 20 kg battery, enabling refueling by battery swap and eliminating range anxiety. A bank of discharged batteries can be recharged whenever local renewable energy is available.

Keywords: Automated vehicles · Microvehicles · Micromobility · Buses · Public transportation · Sustainable energy

1 Introduction

It is feasible to electrify all land transportation [1]. Is it possible to generate the required electricity sustainably? A 1500 kg car carrying an 80 kg person is not sustainable, even if it is electric. Neither is a 17,300 kg bus, which in the U.S. averages 56 l/100 km and carries on average 9 people [2, 3]. On a weight basis, gasoline packs much more energy than batteries, making electric cars heavier. This paper proposes a method to move people in the city using an order of magnitude less energy.

Reducing the required amount of energy used in transportation is critical to mitigate global warming. Energy growth has been greatest in Asia, Africa and the Middle East, with Europe and North America stable [4]. China and India are projected to experience the largest increase in electricity usage through 2050 [5]. It is thus important that the proposed solution can be deployed in developing countries.

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1.1 Energy Overview

Neither electricity nor hydrogen constitutes primary energy; either must be produced from coal, petroleum, natural gas, nuclear, or renewable sources. The main uses of energy are to power buildings, industry and transportation. There are feasible methods to use renewable energy for buildings and industry [6]. Transportation is more problematic. In the U.S., 66% of petroleum goes to transportation [7]. Figure 1 shows that the main consumers are cars and light trucks (gasoline), heavy trucks and buses (diesel) and aviation (jet fuel) [8].

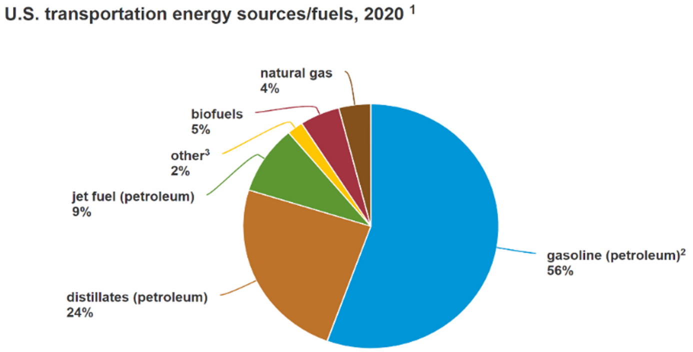

Fig. 1. Most U.S. petroleum goes to gasoline, diesel and jet fuel.

Transportation reform is critical to eliminating liquid fossil fuels. In the Netherlands, 27% of all trips are by bicycle [9]. However, this model seems to have limited transferability elsewhere. In the U.S., bicycle commuting accounts for less than 1% [10]. Asian countries used to have extensive bicycle usage, but the usual pattern is to trade the bike for a motorcycle, and then a car as prosperity improves.

Like a battery, hydrogen offers a method to store energy. Most hydrogen is produced by refactoring natural gas, and has an environmental footprint that is worse than using the gas directly [11]. It is theoretically possible to produce sustainable hydrogen by using renewable energy to electrolyze water, but it is not clear that the process is commercially feasible.

1.2 Energy to Move a Land Vehicle

The power required to move a land vehicle is the sum of energy change to overcome rolling resistance (W_R) plus energy change to overcome aerodynamic drag (W_D) [12]

$$\frac{dW_R}{dt} = \frac{v\sum m}{\eta} g\left[C_R + \frac{s}{100} + \frac{a}{g}\left(1 + \frac{m_W}{\sum m}\right)\right] \tag{1}$$

$$\frac{dW_R}{dt} = k_1 v \sum m \tag{2}$$

v: vehicle speed m: masses of vehicle, riders and baggage

s: % up-slope m_W: effective rotational mass of wheels
a: acceleration g: gravitational acceleration
η: overall mechanical efficiency of transmission
C_R: coefficient of rolling resistance

k_1 is not really a constant, but it includes things over which there is little control or variance.

The equation for overcoming aerodynamic drag is

$$\frac{dW_D}{dt} = \frac{v}{2\eta} A\rho C_D (v + w)^2 \tag{3}$$

$$= \mathrm{k_2 v^3 A\ C_D} \tag{4}$$

v: vehicle speed A: frontal area
ρ: air density w: wind speed (+ headwind; − tailwind)
η: overall mechanical efficiency of transmission
C_D: coefficient of aerodynamic drag

The total energy required when there is no slope or acceleration is

$$E = k_1 v C_R \sum m + k_2 v^3 \mathrm{A} C_D \tag{5}$$

The second term is independent of the mass, and dominates at higher speeds. For heavier vehicles, such as an automobile, the two terms are equal at about 55 km/h; for light vehicles aerodynamic forces dominate above 20 km/h [13]. Thus, streamlining is important for light vehicles, even at slow speeds.

Figure 2 gives the total energy to move a vehicle, showing that a bicycle is vastly more energy efficient than a car [14]. When the bike is converted to a streamlined human-powered vehicle (HPV), the efficiencies are even greater. The figures shown are for a practical commuting HPV, not for a racing HPV.

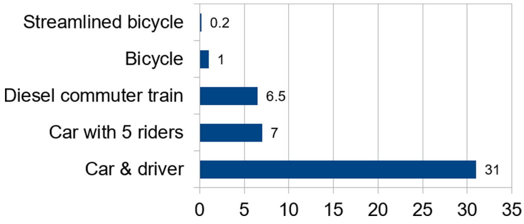

Fig. 2. Total energy consumption at 50 km/h (kW per person)[1]

For 2018, ratings from the U.S. Environmental Protection Agency (EPA) for the efficiency of electric cars varies from 15.5 to 29 kWh/100 km [15]. By contrast, a HPV can achieve 0.69 kWh/100 km [16]. Electrification of transportation is a missed

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[1] The bottom three numbers in Fig. 2 are taken from the table on p. 166 of Wilson, converting kcal/km to kilowatts at 50 km/h. The bicycle energies are taken from the figure on p. 140, reading the power for commuting HPV and utility bicycles at 13.8 m/s.

opportunity if 90% to 99% of the energy is wasted in moving the vehicle instead of the person. Electrifying the entire present vehicle fleet would place demands on the electric grid that would require generation from coal or natural gas. Radical weight reduction of the vehicle fleet will reduce the demand for electricity and eliminate the need for new generating capacity.

Vehicle energy consumption is the same, regardless of whether the energy is generated by human power, gasoline or a battery. Using radical vehicle design, fuel efficiencies equivalent to 0.25 l/100 km (1000 mpg) are feasible.

1.3 Transit Efficiency

Transit's claimed efficiency is based not on fuel consumption, but on other factors. It is argued that transit avoids the infrastructure required to support a large number of single occupancy vehicles. This is modeled as Land Use Efficiency, and also includes avoided automobile trips. The formula used is

$$TransitMultiplier = \frac{T_{eff} + L_{eff}}{T_{eff}} \tag{6}$$

T_{eff}: Transportation efficiency, or reduction of vehicle kilometers travelled from transit passengers

L_{eff}: Land Use Efficiency, or indirect reductions in vehicle kilometers traveled.

The study introducing this methodology claims a Transit Multiplier ranging from 5.97 to 13.04 [17]. This approach is valid for European cities with good public transit where it is feasible to live car-free. It is more questionable for U.S. cities with poor public transportation. It is much easier to live without a car in New York City than in Los Angeles. Some American communities discourage public transit in the belief that it keeps out poor people [18].

Walking, bicycling, and remote work have even better Land Use Efficiency than transit, as illustrated in Fig. 3, which is based on the seldom-achieved ideal of packing 66 people into a bus [19].

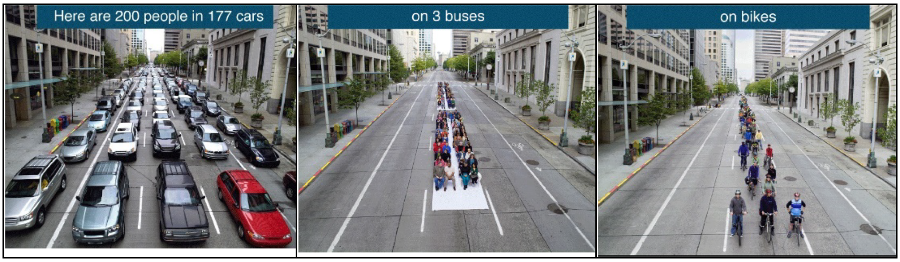

Fig. 3. Street usage for cars, buses and bicycles

1.4 Speeds and the City

Automobile manufacturers would like us to believe that their vehicles operate at over 100 km/h and provide an exhilarating driving experience. In the city, this is rarely the case. The U.S. EPA test for city fuel efficiency is based on an average speed of 34 km/h and 23 stops in an 18 km trip [20]. The Japanese test is based on an average speed of 25 km/h. The New European Driving Cycle includes an Urban Driving Cycle with an average speed of 19 km/h.

Transit doesn't do much better. Proponents of U.S. light rail cite average scheduled speeds of 31 to 42 km/h, with some lines reaching 61 km/h [21]. They concede that bus speeds are 19 to 21 km/h. Seattle's new Link Light Rail system serves a 25 km route from downtown to the airport in 38 min, for an average speed of 39 km/h [22]. Scheduled speeds for Washington D.C. are 48 km/h, but for New York City, it is only 28 km/h [23]. Older lines where the stops are closer together tend to be slower, and newer lines with longer spacing between stops go faster.

Stops for transit passenger pickup and drop-off are unpredictable and delay bus schedules. Loading a wheelchair or bicycle produces even larger delays. Scheduling must deal with time estimates for stops [24].

$$t_d = P_a t_a + P_b + t_{oc} \tag{7}$$

where:

t_d = dwell time (time spent on passenger load and unload);
P_a = number of alighting passengers per bus through the busiest door;
t_a = alighting time per passenger;
P_b = number of boarding passengers per bus through the busiest door;
t_b = passenger boarding time;
t_{oc} = door opening and closing time.

Typical boarding time per passenger is 2 to 3 s, with a minimum of 6 s per stop. It takes 2 to 5 s to open and close the doors. Delay for a wheelchair runs between 60 and 200 s; a bicycle delay is 20 to 30 s. In addition to the dwell time, schedulers must allow 10 to 15 s for the bus to start and travel its own length. The unknowns of whether the bus needs to stop and how many riders will board or exit makes robust scheduling challenging.

1.5 Automated Vehicles

Many of today's systems are hyped as more than they offer, since a fully automated vehicle does not need a driver or safety rider. Two advantages expected from automated vehicles are improved safety and increased road capacity. Fully automated vehicles will never be deployed unless they can demonstrate improved safety. Safety may be achieved by partial automation through Advanced Driver Assistance Systems (ADAS). Connected vehicles provide vehicle to vehicle (V2V), vehicle to infrastructure (V2I), or anything else (V2X) and may be enough to halt the carnage on the roads. The most dangerous transportation mode is the motorcycle, with a fatality rate of 15.92 per 100 M vehicle kilometers travelled compared to 0.58 for a passenger car, a factor of 27 [25]. If traffic accidents become rare, and the car sees the motorcycle even when the driver does not, microvehicles can become nearly as safe as SUVs, especially at city speeds.

Europe and North America have lower traffic accident rates; Africa and Asia higher [26]. The U.N. has projected that by 2025, traffic accidents could be the fifth largest health problem globally. From a humanitarian viewpoint, it may be better to deploy automated vehicles in Asian and African middle and low-income countries as soon as they are demonstrated to be safe. These countries also tend to have lower regulatory barriers.

Automated Vehicles can be choreographed to efficiently operate in platoons, increasing road capacity by two to three times. Close platooning saves fuel, which is one of the main factors behind automation of long-haul trucks. A standard adaptive cruise control (ACC) system has been shown to be inadequate for platoons [27]. A cooperative ACC is needed where vehicle positions and intentions are shared [28]. Existing platooning control systems have difficulties when the inter-vehicle gap becomes small, leading to a jerky and uncomfortable ride. Producing a smooth ride requires increasing the gap, incurring a penalty in road capacity and energy savings.

2 Moving People with Minimal Energy

Based on the considerations of the previous section, the next step is to design a system for moving people in the city with minimum energy. It is necessary to design an entire system, not just a vehicle.

2.1 Design Considerations

Equation (1) dictates that the mass must be kept small. The ideal vehicle has an empty weight less than its riders. An electric bicycle passes this criterion, but Eq. (3) requires an aerodynamic shell when the speed exceeds 20 km/h. The shell also provides protection from weather, extending the conditions under which the vehicle will be used.

The acceleration term in Eq. (1) is a penalty for stop-and-go. The system should be designed so that the vehicle rarely needs to change its velocity. A vehicle that can travel at a constant 50 km/h uses less energy than one that hits 100 km/h but only averages 50 km/h. Vehicle efficiency depends on its operating environment and the two should be designed simultaneously.

Energy consumption is minimized by reducing mass, reducing frontal area, streamlining, minimizing accelerations, and avoiding uphills. Energy is reduced when vehicles travel in platoons with the smallest possible gap between them.

The smallest possible gap is zero, when vehicles travel bumper-to-bumper. There are at least three ways to achieve a gap of zero:

1. Electronic virtual coupling: vehicles are close but not touching.
2. Rigid coupling: vehicles merge to form a single non-articulated vehicle.
3. Articulated coupling: as for railroad cars.

All these methods have been tried, but the problems with the first two make them unsuitable Suppose that a 12-m transit bus seating 40 people were replaced by a road train of 2.4-m-long pods seating two people each. If the bus were carrying 10 people (average U.S. bus occupancy) and the pods had no gaps between them, the platoon would be the same length as the transit bus. If the platoon carried 40 people, it would be four times as long as the transit bus. Virtual coupling of automated vehicles may be done with a headway between vehicles of only 0.5 s, though regulators may insist on more [29]. At 50 km/h, a 0.5-s gap is a spacing of 6.7 m, stretching the platoon to a problematic nine bus lengths. Physical coupling is required to avoid congestion.

Next Future Transportation has a Modular Bus concept with pods carrying 10 passengers and rigidly coupling. This vehicle is about the same size as a transit bus, but does not allow social distancing.

Articulated coupling permits a 48-m bus to move like a snake to negotiate tight turns. However, the mechanical forces on a couple can be large. The French company Modulowatt tried a similar concept in which vehicles mechanically coupled and the lead vehicle towed the others. The system failed because the articulated couples broke [30]. For the concept to succeed, all vehicles must be independently powered and controlled so that there is close to zero force on the couples at all times.

2.2 MilliPod Concept and Operation

The MilliPod™ (patent pending) offers cities a tool to mitigate climate change and improve social justice [31]. It provides faster service, costs less, and uses ten times less energy. It is a train of 2-person, fully-automated electric microvehicles following the bus driver's pod. The MilliPod never needs to stop; it picks up passenger pods on the fly.

A rider would come to a bus stop, then select a destination and pay the fare using a kiosk or smart phone. They would then be assigned to a pod parked at the bus stop, which would unlock for them. The rider has exclusive use of the pod, which may optionally be shared with a companion. A group of riders or a person with extra baggage may rent more than one pod, which will travel together to the selected destination.

As the MilliPod approaches, the passenger pods pull out into the street and begin accelerating to match the speed of the main train. When it passes them, the passenger pods change lanes and gently couple onto the MilliPod. It then continues until the destination, when the passenger pod uncouples, opens a gap between vehicles, then changes lanes and decelerates, parking at the destination bus stop.

The main MilliPod never needs to stop to pick up or discharge passengers, letting it service bus routes faster. The MilliPod carries people, wheelchairs and bikes, but loading is off-line and does not slow the ride. Thus, drivers can cover more distance during their shifts and provide more frequent bus service. Without the uncertainty of passenger load/unload times, schedules can be more reliable. If individual pods break down, they can be taken out of service without affecting the system.

The passenger pods use technology derived from both bicycles and cars, but they have no pedals, no handlebars or steering wheel and no controls operatable by a driver.

COVID-19 has decimated bus ridership [32]. The MilliPod eliminates the need to share space with a stranger, which may help transit agencies recover ridership.

Typical dimensions for the pods are 1.2 m wide and 2.4 m long. This allows the MilliPod to split a standard lane in two, using the outer half-lane as a through lane and the inner half-lane as an acceleration/deceleration lane.

The lead pod is professionally driven. The passenger pods are fully autonomous but only in a limited Operational Driving Domain. Autonomy consists of accelerating to dock with the MilliPod, maintaining position in the train, and uncoupling and decelerating to the destination.

If there are multiple MilliPod routes, the passenger pods will drive themselves to the transfer bus station and then connect with the next MilliPod on that line. If the connection is to a standard bus or train line, the passengers will walk to the transfer point. A MilliPod may provide off-peak service on a route with a standard bus handling high-demand times.

2.3 Energy Efficiency

The target weight for the pod loaded with two male riders is 330 kg. The pods will automatically weigh their loads and an overloaded pod will refuse to operate. A transit bus typically weighs 17,300 kg, a factor of 52 [33]. Rolling resistance is directly proportional to vehicle mass. If the MilliPod consists of 26 pods, it still weighs only half as much as the bus. On a lightly used route serviced by 10 pods, the bus weighs 5 times as much.

A standard bus must stop and start to pick up riders. For the MilliPod, only a few pods need to start or stop. Acceleration is addressed inside the brackets of Eq. (1). On a level road with the mass of the wheels much less than the total mass, the acceleration term is approximately $[C_R + a/g]$. A typical value of C_R for bicycle wheels on asphalt is 0.004; for car tires it is about 0.010 [34]. With no acceleration, a microvehicle uses 2.5 times less energy from this term.

Rolling energy is proportional to mass. At a constant speed, 26 MilliPod units use 5 times less rolling energy than a bus; a 13-unit MilliPod uses 10 times less. If there is acceleration, it dominates the unitless term in the brackets and is multiplied by the weight of the vehicle. If three pods need to decelerate or accelerate at a stop at 0.1 g, the required power is proportional to $3*330*(0.004 + 0.1) = 103$ kg. For a conventional bus, the number is $17{,}300*(0.01 + 0.1) = 1900$ kg, a factor of 18.

Typical drag coefficients are 0.12 for a streamlined velomobile, 0.25 for a modern car or 0.6 to 0.8 for a bus [35]. We expect that the microvehicles would have a drag coefficient of about 0.25 and have four times less frontal area than a bus; thus, energy to overcome drag is about 12 times less for microvehicles. A typical bus has frontal area of 2.5 m wide and 3 m high [36]. The pods will be approximately 1.2 m wide and 1.5 m high. Typical traffic lanes are 3 to 3.7 m wide, and automated vehicles perform better in narrow lanes than do manually driven vehicles, which enables splitting a lane in two.

Equation (5) compares MilliPod efficiency to the bus. For rolling resistance, there is a factor of 2 to 5 for mass and 2.5 times for C_R for a total of 5 to 12.5 times less energy with no acceleration. When the bus needs to stop, the factor can reach 90. Overcoming aerodynamic drag involves a factor of 12, which is relatively more important for the MilliPod because of its reduced weight. These numbers justify the claims of an order of magnitude improvement in energy efficiency.

The MilliPod is designed to operate at a constant 50 km/h without stopping. If it operates in lanes where transit has priority and signals are synchronized with it, it provides the fastest way to move in the city.

2.4 MilliPod Localization and Control System

The lead pod of the MilliPod is generously endowed with Level 2 ADAS to let the driver devote their full attention to safe operation of the system. If any obstacles are observed that would impede operation of the passenger pods, a warning is transmitted and the MilliPod may stop or take other actions to ensure safe operation.

The passenger pods operate at Level 4 automation in a limited Operational Driving Domain. Their control system is illustrated in Fig. 4. The vehicle state minimally consists of position, attitude, velocity, acceleration, weight and the fixed vehicle-specific quantities from Eqs. (1) and (3). At start-up the vehicle state is initialized with its last values, including position and attitude, with velocity and acceleration set to zero. A sensor measures the loaded vehicle mass.

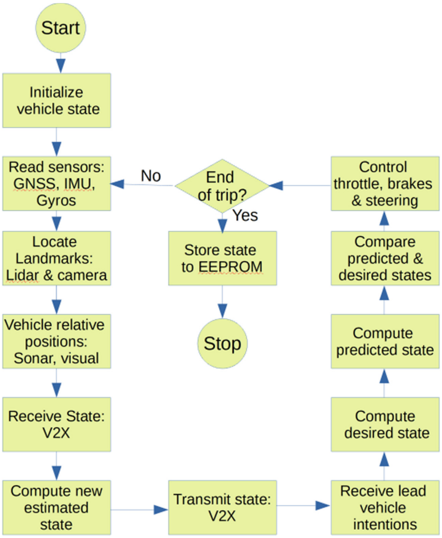

Fig. 4. MilliPod localization and control system

As the vehicle operates, its estimated state is updated by sensors such as Global Network Satellite System (GNSS), Inertial Measurement Units (IMU) and Gyroscopes. These will produce an approximate absolute position, which is made more precise by landmark recognition. Each bus stop will have a distinctive landmark, such as a 5-m-tall orange column. The absolute position of each landmark on the route is known. From the approximate vehicle position, the expected location and size of the landmark in the camera focal plane can be computed. The pod will use visual or Lidar sensors to establish the distance and bearing to the landmark, thus establishing a more accurate absolute position for itself.

As the MilliPod approaches the bus stop, it broadcasts the absolute positions and velocities of the first and last vehicles. The joining pods will then compute the relative distances between themselves and the end of the MilliPod, and accelerate to match its speed and position. When the joining vehicle is in range of the target vehicle, it then uses relative position sensors to dock to the end of the MilliPod. Relative docking sensors can take the form of a known pattern of LEDs on the rear of the target vehicle, which are processed by a position sensing diode, bypassing the complicated computations of machine vision [37]. The algorithm was originally designed for spacecraft docking where there is little interference from ambient light, but we have calculated how to remove that effect. The precise docking information lets the joining vehicle change lanes and smoothly couple to the end of the MilliPod.

If several pods are joining the MilliPod at the same time, they will couple before joining and act as a single vehicle. Once all pods have coupled, they each know their relative positions and can use this information to reconcile the states of all vehicles in the MilliPod.

The passenger pods need to control throttle, brakes and steering so that the MilliPod moves as a single unit but with little or no force on the couples. The couple/bumper assembly contains dampers so that any minor mismatch in force is mechanically absorbed. The couples may contain strain gauges to measure force. Intervehicle force is a damped harmonic oscillator:

$$f = m\ddot{x} + c\dot{x} + kx \tag{8}$$

where m is mass, c is the damping coefficient and k is the spring force. Since mechanical and electrical power are equivalent, force can be sensed from

$$f = \frac{Voltage \times current}{velocity} \tag{9}$$

Variants of Eqs. (1) and (3) are used to predict the expected state changes of each vehicle and the forces on the couples. Equation (9) predicts the required motor current. The lead pod will broadcast any pending application of brakes, throttle or steering before the actions happen; other pods will synchronize with the overall behavior of the MilliPod. The slopes on the route can be accessed from a table indexed by position, filling in one of the variable terms of Eq. (1).

As a pod approaches its destination, it uncouples from the pods ahead and behind it. The pods then open a gap, so that the leaving pod can change to the deceleration lane, and come to a stop at the bus stop. Meanwhile, the uncoupled pods fill the gap and recouple.

2.5 Work Done

In 2011, Dr. Folsom started the open-source Elcano Project to demonstrate that low-cost electronics were sufficient to automate an electric recumbent tricycle (Fig. 5) [38]. His lab at the University of Washington received a grant from Amazon for taking bicycles to automated vehicles [39]. Organic Transit donated an ELF vehicle to the project, shown in

Fig. 5. Automated recumbent Catrike

Fig. 6. Automated organic transit ELF

Fig. 6 [40]. Three full-scale electric tricycles have been converted to automatic operation, with the throttle, brakes and steering controlled by an Arduino 8-bit microcontroller.

Another lab at the University of Washington has converted a 1/10 scale radio control (RC) car into an autonomous robot for indoor use [41]. It is equipped with a more powerful Jetson Nano microprocessor, an Intel RealSense depth camera, and a rotating laser range finder. Dr. Folsom and students are converting the platform for outdoor use, incorporating GNSS, IMU, and vision processing for navigation from landmark detection. The scale models carry the same sensors and electrons as the full-scale prototypes, which have been updated for the Jetson Nano and accessories.

2.6 Future Work

Six 1/10 model cars have been configured to mimic MilliPod operations. It is intended to show that the control system can perform the maneuvers for joining and leaving a platoon and driving bumper-to-bumper. The full-scale trikes will be fitted with the same electronics used in the scale demonstration and put through a similar demonstration. When the feasibility of the operation has been demonstrated, custom vehicles will be designed and constructed. We are looking for partners to demonstrate these vehicles in a transit pilot program.

Including electronics and sensors, the expected price of a passenger pod is $15,000 ± $3,000. Our two recumbent prototype vehicles were built for $3,875 and $4,370. The driver's pod could cost $25,000. About 20 pods would provide the service of a bus. As shown in Table 1, The MilliPod price of $310,000 compares favorably to $550,000 for a diesel bus or $800,000 for electric. The main bus operating costs are driver salary and fuel. The former is the same for the MilliPod and traditional buses. The MilliPod costs much less to fuel than a diesel bus and uses ten times less electricity than an electric bus. Each pod could be powered by a 20 kg battery, enabling battery swap, with the depleted batteries charged from renewable energy.

Table 1. Comparison of buses and the MilliPod

	Diesel bus	Electric bus	8 vehicle MilliPod	31 vehicle MilliPod
Passenger capacity	60	60	14	60
Average ridership	9	9	9	45
kWh/Passenger km	0.600 [42]	0.148 [43]	0.014	0.014
Vehicle cost	$550,000	$800,000	$135,000	$480,000

3 Sustainability and Automated Microvehicles

3.1 MilliPod Extension to First and Last Kilometer

The MilliPod covers bus routes; it is not a solution for the first or last kilometer. The first and last kilometer could be covered by allowing the pods to operate either in automatic mode or be manually driven, with the addition of manual controls for throttle, brakes and steering. A dual mode pod could be operated as a dockless bike or car share. It would be manually driven to the final destination or to a bus stop, where it could join the MilliPod for automatic transportation.

Pods could be privately-owned. They would need to be qualified to be able to fulfill all requirements for the MilliPod and electronically verified when attempting to enter automatic mode.

3.2 Renewable Energy

Ten times less energy requires ten times less battery. The MilliPod has a 20 kg battery, in contrast to the 100 to 544 kg batteries needed for automobiles [44]. The 20 kg battery is expected to provide 30 km of range, which is sufficient for a city trip. Refueling can be done by battery swap. The batteries would be interchangeable and not a permanent part of the vehicle. Batteries can be swapped in less time than it takes to fill a gas tank.

When a MilliPod passenger vehicle senses low charge, it will take itself to a bus stop accommodating battery swap. Batteries take about four hours to charge from standard 110 V circuits. They can be recharged at off-peak hours when grid demand is low. Eventually, recharging bus stops would install wind or solar generators and the batteries can be recharged at any time that renewable energy is available. By contrast, much of the energy to charge cars or buses will often need to be generated from fossil fuels.

The limited battery range is an advantage. It keeps vehicle weight low and energy efficiency high. It is sufficient for the pod to handle one or two trips and take itself to a recharging station. At the recharging station, the pod will be thoroughly cleaned. Any damage or vandalism will be noted and the last riders will be billed for it.

3.3 Self-Driving Micro-Taxis

Eventually, automated vehicle technology will mature to the point that the driver and safety rider are no longer needed. The MilliPod lead pod could then be eliminated.

Automation is an enabler for ultra-light vehicles. If full or partial automation can fulfill its promise of reduced traffic accidents, microvehicles become a safe way to move people around the city at speeds that cars and transit rarely reach. Automation choreographs microvehicles, which could otherwise produce chaotic traffic.

With full automation, pods will no longer need manual controls to handle the first and last kilometers. The pods will evolve into self-driving micro-taxis that can go anywhere in the city without schedules. These will operate on an order of magnitude less energy than automobile taxis and will not require a charging infrastructure. The pods can couple to form platoons with no gaps between vehicles, increasing street capacity.

3.4 Impact

Americans drive five trillion kilometers a year, with 65% classified as urban. The average urban trip is 19 km, making 1.6 trillion kilometers of shorter trips that could be handled by micromobility. Assuming that the micromobility trips use ten times less energy than the trips that they displace, the result is a 32% energy savings. For the United States, this would represent a reduction of 3.8 million barrels of petroleum per day [7]. This translates to 1.6 million metric tons of CO_2 daily [45]. This much CO_2 is equivalent to 43 coal trains [46]. Similar results are expected across the globe.

4 Conclusion

The MilliPod provides faster rides since it never needs to stop. The MilliPod is always the right size for its passenger load and vastly more energy-efficient. It runs entirely on renewable energy and does not pollute. It is expected to cost less than the buses it replaces and is a step to self-driving micro-taxis. It avoids exposure to Covid-19.

Microvehicles traveling at 50 km/h in the city without stopping are faster than cars or buses and use much less energy. Technology can form microvehicles into orderly platoons and lower the cost of city transportation.

In a post-automotive age, automated micro-taxis can become the urban vehicle of choice. Electric automobiles can provide rural and intercity service, but they are too energy hungry to deserve a place in the city.

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