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A Program for Individual Sustainable Mobility

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1. Introduction

Recently we have proposed a new transportation system called PRISM (which stands for Program for Individual Sustainable Mobility) to help alleviate traffic congestion and to improve energy efficiency of travel [1]. The system employs privately owned small, dual-mode vehicles that can run on both conventional streets and a dedicated guideway. In this paper we consider an all-electric version for urban use only. We envision the program beginning as a few isolated systems in large cities and ultimately growing into a national network with high-speed links.

The motivation for considering this system comes in part from studies of traffic congestion. The Texas Transportation Institute (TTI) has reported an analysis of data gathered from 68 US urban areas during 1982-99 [2]. They found that the average annual delay per person increased from 11 hours in 1982 to 36 hours in 1999. TTI estimated the economic cost of wasted time and fuel to be about $78 billion in 1999.

Another consideration is the observation that steady flow at the full capacity of freeways is seldom maintained. A simple estimate can be made for the ideal capacity of a freeway. If we assume a headway time t_h of 1 s and a free-flow velocity v of 120 km/h, the maximum flow can be determined as follows:

$$flow = v / h$$

where the headway is given by

$$h = vt_h + D$$

and $D = 5$ m is the average vehicle length. Substituting values into these equations gives

$$ideal\ \ capacity = 3100\ \ vehicles / h / lane.$$

Typically when the flow reaches about 2500 vehicles/h/lane in free flow, congestion in the form of wide moving jams or synchronized flow (~50 km/h) sets in. The behavior of human drivers apparently leads to instabilities in traffic flow at high vehicle densities and thus congestion [3,4]. The advantage of a system such as PRISM where the cars are under automatic control is that stable flow at maximum freeway speeds can be maintained near the ideal capacity, or higher if shorter headway times and/or platooning are allowed. Also, traffic can be routed by the system controller in a way that maximizes system efficiency rather than the "selfish" interests of the individual drivers.

In addition to reducing congestion, PRISM can increase fuel efficiency and reduce emissions in ways to be discussed. Another important factor is safety: some 90% of traffic collisions are the result of driver error, and removing the driver from control of the vehicle has the potential to dramatically reduce injuries and deaths while driving on the guideway.

While there have been a number of proposals for different types of automated highway systems (AHSs), we believe the unique combination of features characterizing PRISM will help not only to make it economically feasible but also to offer a number of societal benefits as well. Briefly, these features are:

- *A controlled system that requires vehicles traveling on it to meet specified design and inspection/certification criteria.* This makes possible technical, safety, environmental and cost features that would not be possible with an AHS system that accepts many different types of vehicles.
- *Vehicles that are very lightweight (600 kg) and narrow (1300 mm).* This allows a correspondingly light, narrow, and low cost guideway.

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[*] Retired

- *A single lane guideway segregated from conventional traffic.* By restricting traffic to a single lane and allowing merging of traffic streams only at designated points, control is made both simpler and safer. The narrow, lightweight guideway can be fitted into an existing conventional traffic infrastructure in ways that would not be possible with a larger, multi-lane guideway.
- *Electric power supply through inductive coupling to the vehicles.* The single lane guideway and the requirements that PRISM vehicles meet design criteria allow a mechanism to provide continuous coupling of electrical energy to power vehicles traveling on the guideway. This eliminates battery charge-discharge losses, and coupled with the vehicles' small frontal area and ability to platoon, results in excellent fuel efficiency even at high speed. Since the vehicles have unlimited range while on the guideway and leave the guideway with a fully-charged battery, the problem of range that has prevented the commercialization of electric vehicles is largely removed.

Undoubtedly, new electrical generation capacity will be needed to supply power for the PRISM system as it grows. However, new generation plants can be designed to be both efficient and environmentally friendly. Our system therefore offers an alternative to hydrogen-powered vehicles and at the same time offers benefits in terms of congestion relief, speed, and safety that remain unchanged by the substitution of power plants, however environmentally friendly, in conventional vehicles.

2. Overview

Automated highway systems would appear to offer many advantages over today's conventional highway system, some of which have been mentioned above. Nevertheless, there are formidable barriers to their introduction, two interrelated ones being the problem of siting a new infrastructure in the presence of an existing one, and the "chicken and egg" problem – how can infrastructure and the cars that use it grow symbiotically? The system we describe in this paper has been conceived with these two considerations in mind. To address the first question we propose a system whose vehicles are as small, lightweight and narrow as possible to allow a correspondingly narrow, lightweight, and low-cost guideway which can be most easily fitted into the medians or buffer zones of existing expressways. To address the second issue we suggest that the system begin as separate entities that serve commuters in localized regions. If designed to appeal to the needs of commuters, such systems can be viable even if unconnected with each other. As the user base grows, we expect infrastructure to spread and eventually interconnect to form a nationwide network.

In addressing the first goal, we have conceived of PRISM vehicles as small, lightweight (600 kg) cars that hold two occupants in a tandem seating arrangement. While a car of this type runs counter to recent trends towards large vehicles, we believe that it offers a number of compelling advantages in the environment in which the system will operate.

- Occupancy for U.S. commuters is about 1.2 persons per vehicle. Thus for the majority of commuters the lack of space for more than one passenger will be of little consequence. When the vehicle is on the guideway, the driver's seat may be able to swivel around allowing face-to-face communication with a passenger or giving the driver access to an in-car office.
- The tandem seating arrangement permits a vehicle with small frontal area. This reduces drag and permits very good energy efficiency even at high speed, especially when the vehicles are platooned.
- In an urban environment where space is at a premium a correspondingly narrow, lightweight guideway is more easily accommodated and has less visual impact than a highway-size structure. Not only is it easier to find space in medians or borders of existing highways, the construction cost of the guideway is reduced, especially in areas where it must be elevated or placed underground.
- Off the guideway, the small size of the vehicles helps to reduce traffic congestion and permits high-density parking, especially if the automated driving capability is used to allow the vehicles to park themselves in special sections of parking garages.
- The low weight of the vehicles and their low drag result in excellent fuel economy in conventional driving as well.

- The tandem seating arrangement permits more crush space in the event of a side-impact when off the guideway than would be the case for two-abreast seating. The narrow front can help in frontal crashes as well, allowing the vehicle to partially offset its low-weight disadvantage by more penetration into the impacted structure.
- Low placement of battery and electric motors, coupled with active stability control and possibly with active steering, can result in a stable vehicle.

To address the "chicken and egg" issue, a way must be found to induce consumers to purchase/lease vehicles even when the AHS infrastructure is very limited. One approach that has been suggested is to offer "AHS ready" vehicles, vehicles with such features as drive-by-wire and advanced communication systems that may be upgraded at some later time to full AHS capability. This strategy relies on the usefulness of these features to be high enough even in the absence of AHS infrastructure that the consumer is willing to pay the substantial extra cost. An alternative approach, which we advocate here, is to make the AHS system sufficiently attractive to some fraction of drivers that they will purchase vehicles even with very limited infrastructure. To this end, commuters form an ideal market. A commuter may find the PRISM system useful as long as there is a guideway between house and destination, even if that is the only route on which the automated features of the car can be used. Aimed at the commuter, the system should offer freedom from congestion, reliability, safety, and low emissions, with high speed an attractive, but not necessary, feature. (Low emissions and other societal-benefit features may be a very desirable from the standpoint of the government entities whose support for the system is vital.)

Outside of the urban environment, congestion may be less of an issue. We suggest that here a PRISM system can offer another benefit to the potential user – high speed. By platooning vehicles, air drag, the major drag force at high speed, can be significantly reduced, allowing good energy efficiency even at elevated speeds. In such a way, PRISM can be time competitive with short-haul airlines on a door-to-door basis, in addition to offering a single-mode form of travel.

3. System Description

Vehicles

When on the guideway the vehicles are capable of full drive-by-wire operation. Each vehicle carries sensors that enable it to follow the correct path down the guideway. The sensors can take any of several forms, and can be combined if desired for redundancy. We describe three schemes:

- The pickup that inductively couples power to the vehicle, described later, is kept centered around the supply cable by both active and passive means. This allows the distance of the car from the cable to be easily measured. An exiting or entering car is briefly disconnected from the power cable so an alternative sensing means must be employed during these times, or more simply, the car can rely on inertial guidance during these short periods.[*]
- The distance of the car to either or both walls can be measured optically or ultrasonically. At entrances and exits, through cars would follow the left wall and merging or exiting cars would track the right wall.
- Flux-gate magnetometer sensors can detect magnets buried at intervals of a meter or so along the guideway. This method has been pioneered by the California PATH group and allows static codes (by alternating the polarity of the magnets) to mark upcoming exits [5].

PRISM vehicles will measure the distance to the car ahead with forward-looking radar, similar to today' s Intelligent Cruise Control. Target discrimination will be much simpler than for conventional traffic, however, because there is only a single lane of traffic and because cars can incorporate retro-reflectors by design. Vehicles will be able to communicate with the cars directly in front of and behind them. As a result, they can receive information as to the number of vehicles in a platoon, and when in a platoon, receive information about the actions of the lead vehicle (and other vehicles). Having this knowledge has been shown to greatly increase the stability of a platoon [6].

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[*] Micromachined silicon inertial guidance devices are available today that are adequate for such purposes and can be manufactured at very low cost.

Vehicles will be powered by electric motors. While driving on the guideway they receive power continuously through their inductive coupling. Because this power can also be used to charge an on-board battery, vehicles leave the guideway with a fully charged battery.

Figure 1 shows two cross-sections of the inductive coupling apparatus. (See also Figure 2 for a view of the system installed in the guideway.) The design is based on an idea by Divan, et al [7], but includes a Halbach magnet array to passively aid in centering the pickup around the power distribution rod as the vehicle moves.

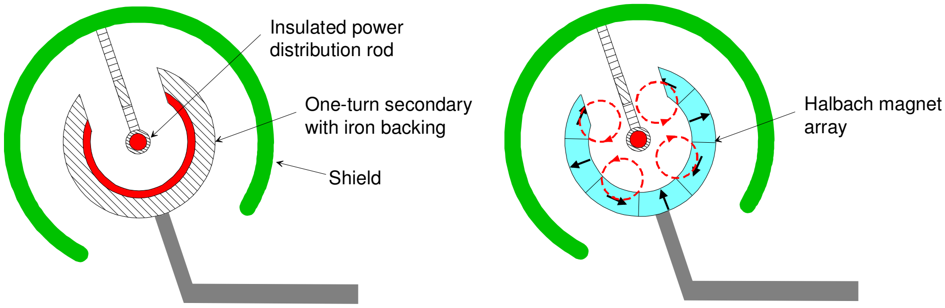

Fig. 1. Cross sections of power distribution rod and shield, and inductive coupling pickup apparatus. Left: Inductive pickup. Right: Halbach magnet array to provide passive centering and reduce the requirements of a supplemental active control system (not shown). The pickup and magnet array are mounted on the same support rod, attached to the vehicle.

Guideways

A guideway cross-section is shown in Figure 2. To make the guideway as lightweight as possible, the running surface comprises two strips separated by an open space covered only by a gridwork. Walls on either side prevent entry of animals and debris in non-elevated sections, reduce sound radiation, and would contain a vehicle in the event of a control failure.* On the left wall is the cable that provides power to the vehicle. The cable is almost completely surrounded by a coaxial shield, with only a downward oriented slot through which the control arm of the vehicle' s inductive pickup fits. The shield is opened up somewhat at exits and entrances to allow the pickup coil to disengage from the cable.

Power is fed to the power distribution cable by substations located at intervals of 1 to 10 km along the guideway depending upon vehicle flow. The distribution cable is expected to operate at a frequency of about 2 kHz with a voltage excitation of about 6 kV.

The total width of the guideway is just over 2 m, i.e., just over half the width of a standard 12-ft highway lane. This narrow width facilitates the placing of the guideway in urban environments, either in the medians or along the buffer zones of existing highways. Where there is no room, the guideway can be elevated or placed in small tunnels. In less densely populated areas, the guideway can comprise two or three lanes (separated by walls) and handle traffic in both directions. The optional center lane carries traffic in either direction when one of the two outer lanes is temporarily shut down as a result of a blockage or for maintenance.

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[*] Note that because of the narrow width of the guideway, even an out-of-control vehicle is kept on course with no structures that can be hit at more than a glancing angle.

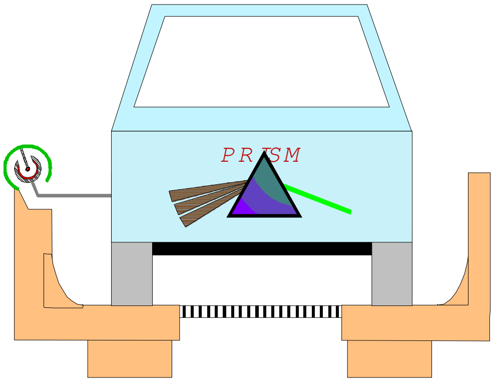

Fig. 2. Cross-section of PRISM guideway showing shielded power supply cable and open gridwork between the tire strips

Once on the guideway, cars travel at a system-designated speed. So as not to impede the efficient flow of through traffic, all acceleration and deceleration takes place on entrance and exit ramps. A typical entrance ramp is shown in Figure 3. In an intercity system, which is expected to operate at higher speeds (~200 kph) than the urban system described here, vehicles will have sufficient power to maintain speed in platoons, but may be underpowered in their ability to accelerate to that speed in a short distance. This could lead to unduly long entrance ramps. While this is less of a concern in the urban system, the solution proposed in the intercity version could be employed in cases where space for entrance ramps is very scarce. In that system, linear induction motors (LIMs) are used to boost the acceleration of cars on the entrance ramps, as shown in Figure 4. In one version, cars carry passive reaction plates (iron-backed aluminum), which form the secondary of a LIM whose stationary primary is located in the acceleration lane. The acceleration lane is divided into several sections, each with its own LIM. An accelerating car is handed off from one section to the next as it accelerates, and thus as many cars as there are sections can occupy the entrance ramp at the same time. In another version of this same scheme, the reaction plates are located on carts riding on rails in a channel along the acceleration strip. The carts mechanically engage the PRISM cars and accelerate them to full speed before returning the start to be used again.

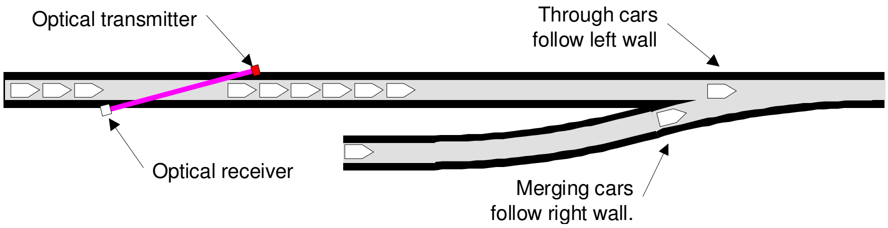

Fig. 3. PRISM entrance ramp

Cars will be subject to strict maintenance procedures, so mechanical breakdown will be rare, but not non-existent. In most cases, a disabled car can be towed off the guideway by a special maintenance vehicle. Alternatively, the lightweight vehicles can be designed to be easily lifted over the guideway wall by a mobile boom, even from an elevated structure. In areas where a three-lane guideway exists, most following traffic would be diverted to the center lane, bypassing the blocking car. Automated snow throwers can traverse the guideway to keep it clear of snow accumulation.

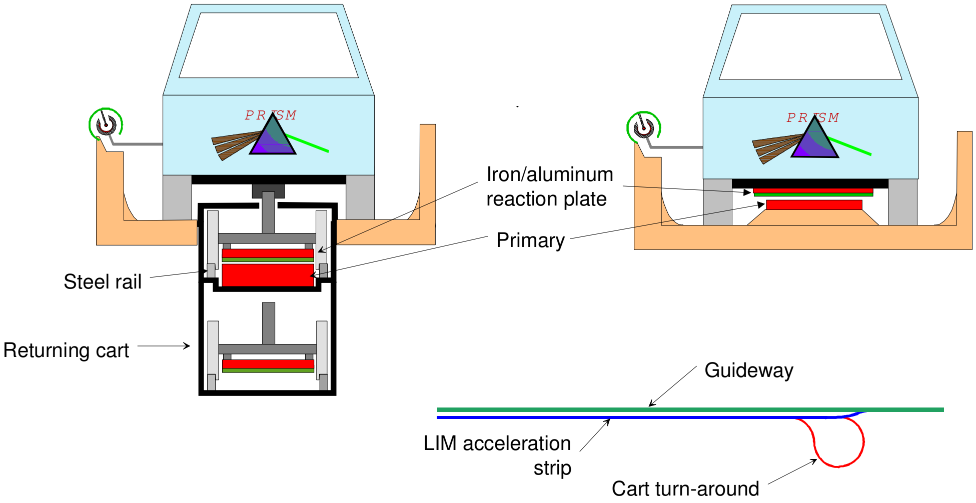

Fig. 4. LIM acceleration boosters, separate cart and integrated into the vehicle

We have estimated the cost of a guideway based on detailed estimates and actual construction costs of earlier short-distance guideway projects that one of us (Pacheco) has managed. We estimate the cost of a single-lane PRISM guideway, excluding access ramps but including electrical distribution, to be about \$1.0–1.2M/km, the larger figure based on standard construction techniques and the lower figure using innovative techniques suitable for mass production. A corresponding range for an elevated guideway is about \$2.0–2.4M/km. These figures are similar to the cost of a Personal Rapid Transit guideway [8], and significantly less than the \$5.6M/lane-km estimated by PATH for an elevated two-lane AHS guideway [9].[*] For an underground system we estimate tunneling costs at \$1.1-1.3M/km plus the cost of the guideway itself for a total of \$2.1-2.5M/km, only slightly greater than that for an elevated system. Tunneling may be an attractive option in situations where an above-ground system involves large ancillary costs such as bridge rebuilding, or where there is a desire to avoid an elevated structure for societal or other reasons.

Control

Control of the PRISM system is distributed among three levels. At the lowest level is the computer in each vehicle, which is responsible for guiding the vehicle and controlling its position relative to other cars, including joining and exiting from platoons. For example, a car within a platoon that wishes to exit (and has been given permission by the cell controller, see later) will signal its intent to the other vehicles in the platoon. The following vehicles will open up sufficient space to allow the car to exit the platoon, after which the leading vehicles will slow momentarily to allow the platoon to re-close. Any car that detects an anomaly will signal both the cell controller and the cars around it and indicate if it is applying emergency braking.

At the next level are cell controllers, which are responsible for maintaining traffic within a cell. A guideway cell is a portion of the guideway bounded by entrance and exit ramps (or between lane crossovers in the case of a three-lane guideway). The cell controllers control the entering and exiting of vehicles. They track the position of vehicles and platoons within their jurisdiction and issue commands to the vehicles to open up space as necessary to allow entering vehicles to merge seamlessly. They also respond to emergencies by shutting down entrance ramps and/or diverting traffic to another lane. A car wishing to enter the guideway is interrogated by the controller to verify that its certification is up to date.

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[*] An inflation adjustment factor of 20% has been applied to the 1994 cost estimate. It might be noted that the PATH guideway construction cost estimate is only about 50% of the total estimated cost. Other costs include construction of access ramps, construction support and detours, land acquisition, and contingencies. A narrow, easily fabricated PRISM guideway should minimize these costs as well.

In Figure 3 the cell controller has opened a space for entering cars to merge. The open space is verified by an optical (or other) sensor, and the entering car has been commanded to accelerate so as to merge into the opening as it passes.

At the highest level are regional controllers, which monitor the conditions of traffic both on the guideway and, through connections with existing traffic monitoring systems, on connecting conventional streets. If traffic is congested at a particular exit, for example, the controllers may require guideway traffic to bypass that exit. A car wishing to enter the guideway will provide the controller its intended destination and will be informed by the controller if any problem is anticipated before it enters.

4. PRISM Environmental Benefits

Because PRISM vehicles are electrically powered, they will generate no local emissions either on or off the guideway. New electrical generation capacity will probably have to be constructed to provide the power, and these new power plants can take advantage of the latest technology to reduce emissions and improve generation efficiency. For example, while the present average U.S. power generation efficiency is only about 32%, natural-gas fired combined cycle turbine power plants will have efficiencies on the order of 55% [10]. The vehicles' low air drag (particularly when reduced by platooning, which can yield drag reductions of as much as 60% [11]), lack of battery charge/discharge losses and constant speed operation while on the guideway combine to give extremely good energy efficiency even at high speeds. Table 1 shows energy efficiencies and CO_2 emissions for mid-size advanced hybrid vehicles as estimated by Weiss, et al [12], a current Toyota electric (battery-powered) vehicle, and an electric PRISM vehicle. If these predictions for PRISM are realized, substantial improvements over other advanced vehicles can be obtained.

Technology	*Energy consumption MJ/km*		*CO_2 emission well-to-wheels gC equiv. per km*
	Direct	*Well-to-wheels*	
2001 reference (30.6 mpg gasoline)	2.47	2.99	61
2020 advanced SI hybrid (gasoline)	1.07	1.29	26
2020 advanced diesel hybrid	0.92	1.05	22
2020 hydrogen fuel cell hybrid	0.59	1.05	21
Toyota RAV4 electric vehicle	0.67 [13]	2.16[*]	31[*]
PRISM electric car[†]	0.36	0.72	10

Table 1. Energy consumption and CO_2 emission (carbon equivalent) for various vehicle technologies. "Well to wheels" energy consumption includes the energy cost of producing and distributing the fuels.

5. Conclusions

The PRISM system offers potential benefits in terms of congestion relief, safety, and speed, while at the same time offering environment benefits that surpass estimates for advanced hybrid vehicles. There are nevertheless barriers to its implementation, most importantly the need to construct a guideway

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[*] Based on the present U.S. power generation mix. Since the PRISM primary energy projections are based on a future generation efficiency, comparison to PRISM data is not a fair "apples to apples" comparison, but rather is meant to illustrate the improvements that can be achieved by utilizing both smaller vehicles and more efficient power generation.

[†] The calculations assume travel on the guideway at a constant 130 km/hr, an accessory load of 1000 W, a drag coefficient of 0.32, and a reduction in air drag of 40% from platooning. Electric machine efficiency is assumed to be 94%, inverter efficiency 97%, and transformer efficiency 91%. The latter efficiency includes an estimate of 5% loss from eddy current drag. Well-to-wheels energy and carbon emissions are calculated on the basis of a natural gas fired combined-cycle turbine power plant operating at an efficiency of 55% with distribution losses of 9%.

infrastructure. The approach of concentrating in the beginning exclusively on commuter vehicles is based on making a limited infrastructure appealing to consumers whose commute path can take advantage of a specific section of guideway, even in the absence of an interconnected system. The small vehicle size assists the placement of guideways in densely populated areas, but may ultimately limit the appeal of the system to commuters and others who do not need to carry greater numbers of either people or goods. However, the single-lane nature of the guideway lends itself to a system capable of accommodating vehicles of larger size in the future. Larger-width lanes for larger vehicles, including commercial trucks, could be built alongside the small vehicle lanes, segregating traffic for safety. Space for these larger guideway lanes may become available even in urban areas as the benefits of the system are demonstrated, and existing highway lanes can be converted to guideway use.

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