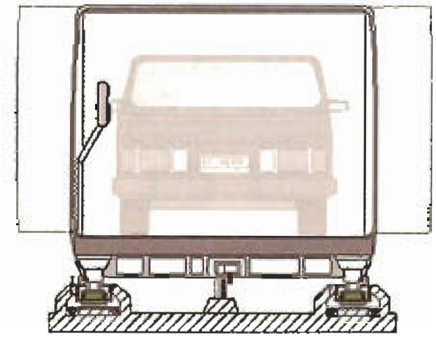
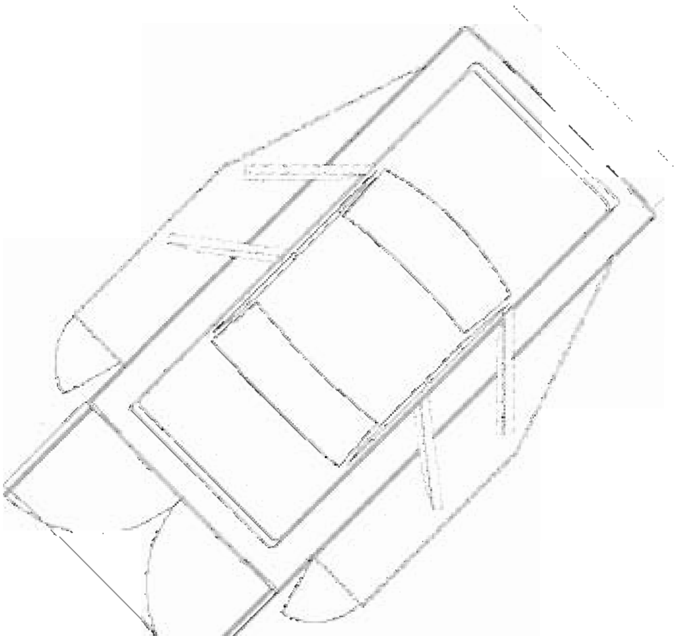


INTERMODAL INNOVATION

Using maglev technology, transportation engineers may one day offer an alternative to motorists who want to avoid congested highways without giving up their automobiles.

Andreas Steingröver, Rasmus Krevet, and Robert L. Bertini



AUTOSHUTTLE WOULD *transport road vehicles with their passengers in ventilated transparent cabins.*

Imagine you are driving down a congested freeway. An exit lane leads you to a station for a magnetically levitated (maglev) intermodal transportation system. There you drive your car into a transparent cabin. Soon your cabin enters a convoy traveling at a constant speed of 112 mph (180 km/h) alongside the freeway. During the journey you pay the low fare with your credit card. You may change your desired destination using a voice recognition module. Upon reaching your exit, the cabin switches out of the convoy and brakes automatically. The front door then opens and you drive out of the cabin and continue your trip.

A 3.3 ton (3 Mg) prototype maglev vehicle has already been built for such a system—called Autoshuttle—at the Technical University of Braunschweig, in Germany. Compared with other methods that have been proposed for transporting vehicles on an individual basis, this intermodal system demonstrates a high degree of safety, environmental friendliness, and economy.

Recent traffic predictions indicate that motor vehicles will dominate future travel volumes because of

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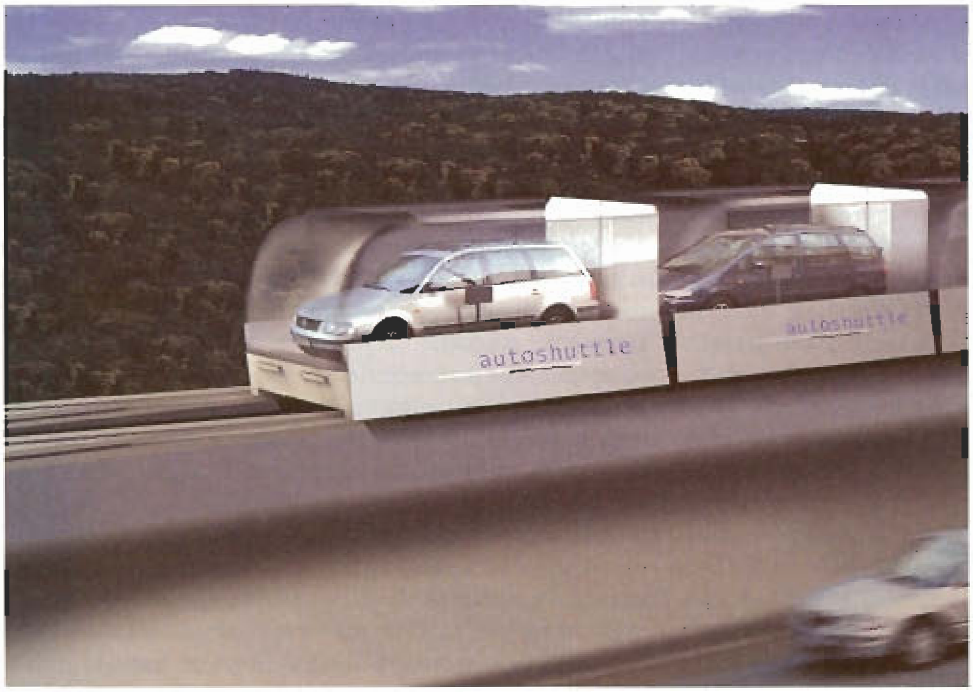


CABINS TRAVEL *in high-speed convoys along a maglev guideway adjacent to an existing highway.*

the flexibility, comfort, and generally acceptable cost of road transportation. Road users will feel the effects of this principally through increasing congestion and accident risks. Roadside residents and the environment will suffer by losing the physical space that roadways will require. Neighborhoods will be intersected, and there will of course be the attendant noise, energy consumption, emissions, and accident risks.

Alternatives that depart from the common practice of individually operated highway vehicles moving on major transportation arteries have been proposed in the past. Railroad cars for transporting cars and trucks theoretically require less space than roadways. With the operating schemes realized so far, however, the time-consuming, costly loading and unloading of the trains, combined with either the low station density or low average speed because of frequent stops, would limit the potential traffic volumes on those systems. Additionally, the energy savings obtained from rail are quickly absorbed if patronage is poor or if the travel speed is considerably higher than the typical road traffic speed.

Another proposed system involves dual-mode vehicles, with conventional rubber tires for highway operation and an additional suspension system for track guidance. This type of system would have little effect on energy consumption. Another disadvantage is the need for specially designed vehicles.

An alternative solution is the convoy concept developed by Volkswagen during the 1980s for heavily used freeways. A similar system was demonstrated in the United States in 1997 as part of the National Automated Highway System Consortium. With this concept, the driver enters the slow (right-hand) freeway lane and transfers control of the car to a computer by pushing a button. The car is steered to the passing (left-hand) lane and joins the front of a "platoon." Using sensors, the cars follow one another at a distance of 7 ft (2 m). The driver requests an exit by pushing another button, and the car leaves the platoon by moving toward the right lane. The driver then resumes control of the car. The vehicles following automatically close the gap in the platoon. This system increases freeway capacity and reduces air resistance, but unfortunately safety problems remain unresolved. For instance, if a vehicle in the platoon experiences a flat tire and goes out of control, the vehicle following may be affected.

The safety problems of automated platoons made up of highway vehicles are avoided if vehicles are transported by maglev track-guided cabins. Passengers may remain seated in their vehicles. In the Autoshuttle system, the cabin body and the hinged front exit door are transparent, while the two laterally hinged rear entry doors and the floor are opaque. Solar cells could be mounted on the roof to cool the cabin if necessary. During the convoy journey each cabin joins directly to the end of the preceding cabin. Since the cabins fit together in modular fashion, a streamlined cabin-to-cabin connection is achieved. The cabin sides pivot to form auxiliary doors so that the passengers may leave the cabin in extraordinary circumstances. Effective ventilation is also provided.

The cabins for passenger cars have a small cross section, with an internal width of 7.2 ft (2.2 m) and an internal height of 5.6 ft (1.7 m), while those for trucks and buses have a larger cross section—10.8 ft (3.3 m) internal width and 14.1 ft (4.3 m) internal height. Both types have different internal lengths—from 11.8 to 18.4 ft (3.6 to 5.6 m) for cars and from 20 to 62 ft (6 to 19 m) for trucks and buses. All types ride on the same track, and cabins with identical cross sections form convoys.

The typical operating speed is 112 mph (180 km/h) for all convoys. The uniform speed yields an optimal line capacity. This speed is below what is technically possible but is sufficient to make Autoshuttle transportation clearly faster than conventional highway travel. At this speed, energy consumption is very low, noise is almost negligible, and a relatively sharp guideway curvature—a minimum radius of 4,100 ft (1,250 m)—is acceptable. In extremely congested areas a speed reduction would be possible in order to combine Autoshuttle with any very sharp curves in an existing highway right-of-way. A convoy can travel a gradient of 10 percent at a constant 112 mph (180 km/h), so ramps can be shorter than typical highway ramps.

Inside the cabin a flat communication module automatically moves toward the driver's opened window. The driver uses the communication module to give the desired exit station by voice command or keyboard. Alternatively, a cellular phone can be used for this purpose. The type of highway vehicle is determined by the system at the entrance station by a license-plate identification system linked to a vehicle registration database. The fare is calculated based on vehicle type and is lower than the corresponding operating cost, including fuel and wear and tear. The highway vehicle's dimensions are determined by light-beam detectors so that a suitable cabin is ordered. A fast exit button for exiting at the next station, an emergency call phone, a power supply for the highway vehicle's equipment, and cabin ventilation control are also provided to the driver.

Stations are located approximately 3 mi (5 km) apart, on the order of freeway interchange spacing, and are configured as shown in figure 1. An exiting cabin leaves the convoy via a passive switch. The cabin brakes on a 0.6 mi (1 km) deceleration track, turns to the right, and stops in an exit bay, where the highway vehicle leaves the cabin through the front door under its own power. The cabin then moves backward toward an entrance bay, where it awaits the entry of another highway vehicle. As soon as a convoy has reached a reference position on the main track, the freshly loaded cabin accelerates, switches onto the main track via a passive switch, and is swiftly caught by the convoy upon reaching the operating speed. The cabins that do not wish to exit pass the station at full speed. The car convoys follow one another at two-minute headways, while truck and bus convoys run on six-minute headways. The frequency would decrease during the off-peak hours. Physical coupling of the cabins is in principle not necessary, but simple engaging couplers that uncouple using lateral motion are provided. The convoy need not be expanded when a cabin leaves the convoy at the passive switch. At interchanges the cabins can change Autoshuttle lines automatically.

The magnetic levitation and guidance system consists of two upside-down L-shaped rails on each side of the cabin. The levitation systems of the cabins enter between the two rails on each side and engage from beneath the rails. A permanent magnet with surrounding excitation coils forms symmetric magnetic circuits with minimized energy consumption. The magnetic field in the cabin is very low, comparable to that of the earth. The configuration of the levitation system makes levitation possible even when one rail per side is omitted. This is the case on some parts of the passive switch, as shown in figure 2.

Additionally, lateral movement control magnets are activated for short periods when a cabin enters a passive switch. For example, cabins turning to the left activate these magnets so that the other cabins stay on their intended path. A cabin exiting to the right travels contact-free by its on-board magnet along the right-hand branch of the passive switch.

As an additional mechanical safety device, vertical guidance rails are mounted at the switch in the center of both the straight and the deviating branches. Under the cabin at the front end is a guidance pin that can move laterally. A cabin approaching a diversion point determines its intended direction before reaching the braking distance of the switch by activating the lateral motion magnet and moving the guidance pin. The pin is latched at the desired position. An emergency brake is applied on failure. The guidance pin travels laterally without contact along the guidance rails. Erroneous guidance is not possible even in the case of magnet failure because of this mechanical safety device. Therefore, the safety standard of this passive switch is at least as high as that of conventional railroad switches.

Autoshuttle has a long-stator linear synchronous drive with an iron-free stator winding placed beneath the rails on each side of the track. In track sections where cabins move very close to one another at different speeds, motor sections can be shortened—down to 8.9 ft (2.7 m). The motor has a simple configuration and attains high efficiencies because of the low power demand of the convoys at constant speed and the short motor sections during the accelerated motion. Power demand reaches 45 kW/ft

A convenient first application could be U.S. 101 between San Francisco and San Jose, California—a busy 47-mile corridor carrying about 200,000 vehicles per day.

(150 kW/m) to accelerate a cabin containing a heavy truck. During travel at constant speed, the power demand falls to approximately 1.2 kW/ft (4 kW/m) for a heavy truck cabin and 0.75 kW/ft (2.5 kW/m) for a passenger car cabin.

The individual control of the short motor sections makes the rendezvous maneuver possible. The control principle becomes quite simple if predetermined curves for the movements of the approaching vehicles are used. The motor control corrects small deviations. Only larger disturbances or defective motor sections require an adaptation of the predetermined curve.

Communication between the cabins and the control center takes place by radio or a cable in the track bed. The control center receives information from the cabins on position, desired exit station, and fare, along with information in the event of emergencies and failures. The cabins in turn receive information from the control center on the direction to be chosen at the next passive switch, the fare for the transported highway vehicle, and what to do in the event of an emergency.

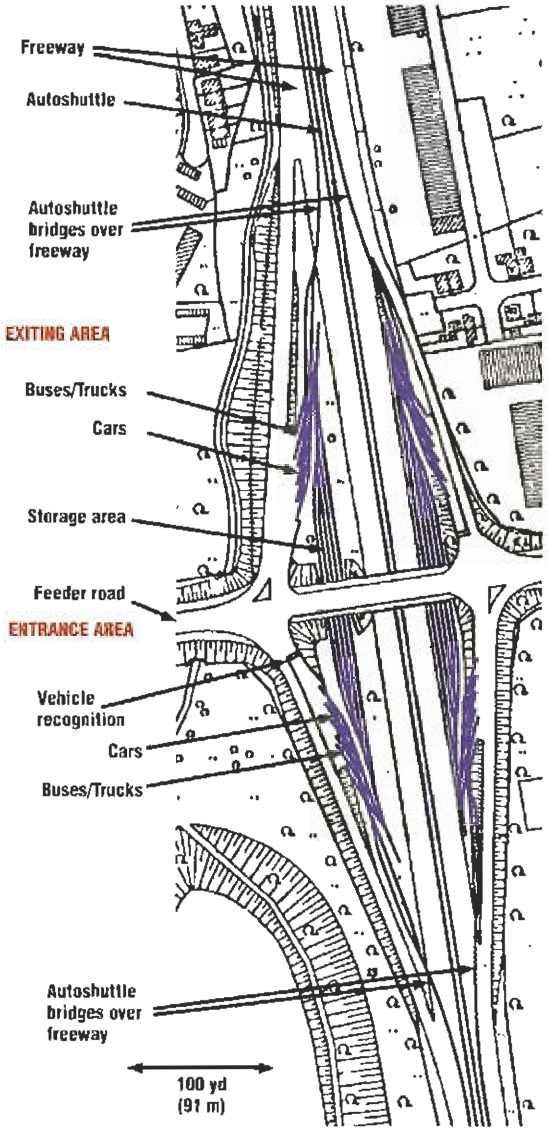
The control center processes the information received from the vehicles and furnishes appropriate direction commands to the cabins. The track incorporates sensors to detect the presence of cabins. If the sensors detect that a vehicle is for whatever reason lagging behind its calculated position, all following cabins, whose positions could conflict with that of the lagging cabin, will be braked after a tolerance interval. The control center calculates track occupancy after the passage of a passive switch according to the desired destinations of the cabins. Indications of desired exit stations are used to coordinate the empty runs required for dispatching the necessary number of cabins to each station. In addition, a time- and date-dependent forecasting program is used for this purpose.

Autoshuttle's energy consumption includes cabin consumption arising from air resistance, eddy current losses in the rails, inductive energy transmission for on-board equipment, and infrastructure energy consumption.

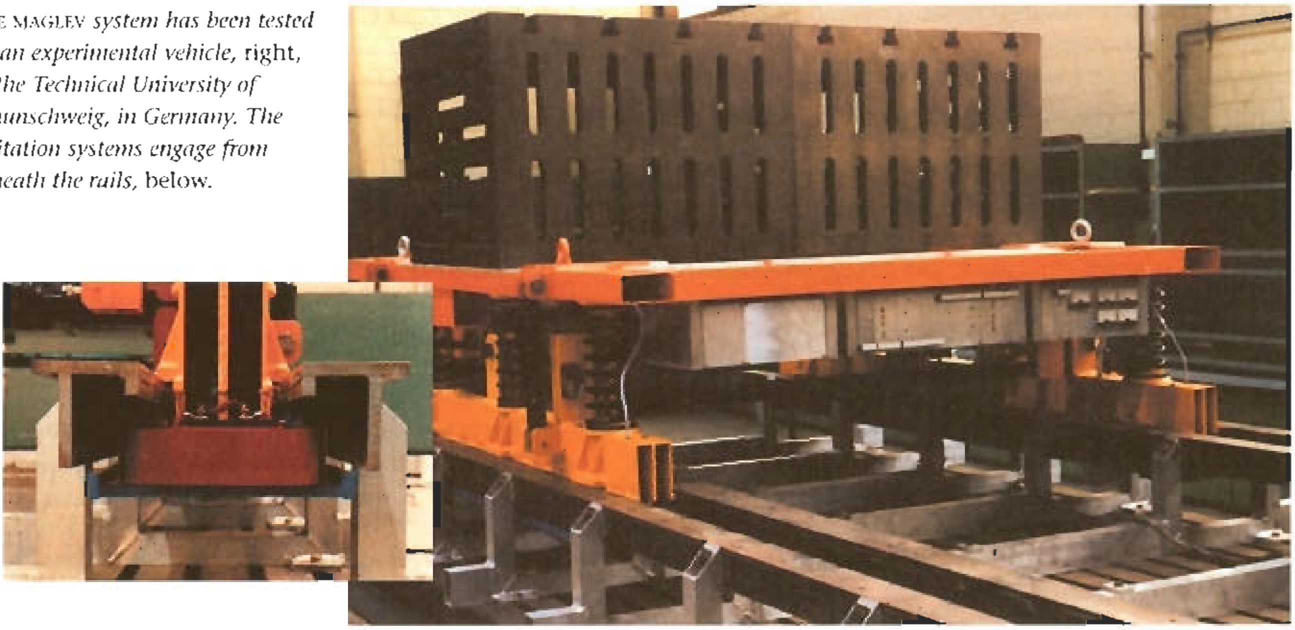
Air resistance has been calculated by applying an air resistance formula for rail vehicles and by numerical analysis using aerodynamic similarity to an existing Transrapid maglev vehicle in Germany. Both methods yield an aerodynamic resistance coefficient of 0.69 for a 581 ft (177 m) long convoy with 38 cabins for cars. This assumes a 62.4 sq ft (5.8 m^2) cross section and an average cabin length of 15.1 ft (4.6 m); it also assumes that an empty tail car with a streamlined form could be added at the end of the convoy. The value diminishes for shorter convoys and reaches 0.28 for a single cabin. Eddy current losses in the rails strongly depend on the choice of material and the distances between the cabin-borne supporting and guiding elements of each cabin during the journey in a convoy.

On-board energy demand includes the highway vehicle's equipment, the levitation system, the communication module, and the cabin window control. The highway vehicle has power demands for heating, ventilation, and other equipment of approximately 1.5 kW. The levitation system for a

Fig. 1 Station Layout



THE MAGLEV *system has been tested on an experimental vehicle,* right, *at the Technical University of Braunschweig, in Germany. The levitation systems engage from beneath the rails,* below.



vehicle with an empty weight of 3.3 tons (3 Mg) and a load of 2.2 tons (2 Mg) demands 1 kW. Other on-board equipment demands an average of 0.2 kW. Average on-board equipment consumption therefore totals 2.7 kW.

To calculate energy efficiency, a typical journey with the following parameters was examined: a journey length of 22 mi (35 km); an acceleration phase with several cabins starting together; exits located every 3 mi (5 km), at which every tenth cabin leaves the convoy; and a braking phase with cabins traveling individually. Empty runs to dispatch the cabins were also included in the calculation. In the acceleration phase, an empty cabin was treated as an additional cabin behind occupied cabins. Other parameters were the same as for occupied cabins but with no on-board highway vehicle energy consumption. Every 3 mi (5 km) there is a station that demands 20 kW of power for illumination, cabin door actuation, shunting movements, and optical recognition systems.

For a typical journey, motor energy efficiency varies between a short-term value of 70 percent during braking and 91 percent during travel at a constant 112 mph (180 km/h) on level terrain. The average efficiency of energy transmission from the power plant to the levitation system is assumed to be 32 percent. These calculations yield a primary energy consumption of 24 kWh per average car per 62 mi (100 km), or the equivalent of 102 mpg (43 km/L) of diesel fuel. Analogous considerations yield, for example, 18 mpg (8 km/L) for a 59 ft (18 m) truck. Assuming that electric power is furnished by coal, gas, or fuel oil power plants and that long-distance heat supply is realized, the primary energy consumption may be further reduced by 40 percent.

Autoshuttle's emissions were compared with those from ordinary auto traffic and from intercity express trains in Germany. Patronage was assumed to be 1.1 passengers per car for both Autoshuttle and road traffic. Autoshuttle's emissions were much lower than those for cars and equal to those for high-speed trains.

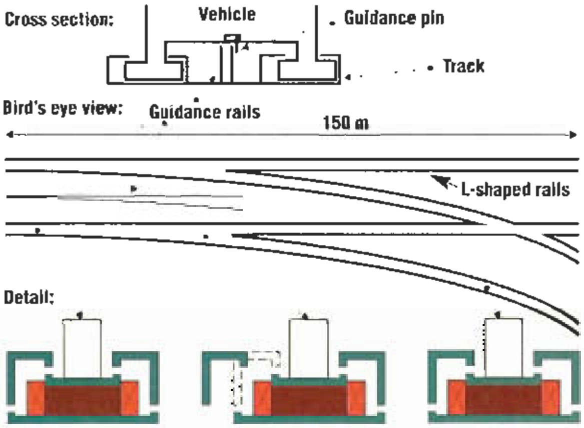
Based on measurements made on an experimental Transrapid maglev vehicle, convoy noise emissions of less than 74 dB at a distance of 82 ft (25 m) can be expected. With typical convoy frequencies this yields a very low average noise level, making noise reduction measures generally unnecessary.

At capacity, the main line is fully engaged by convoys except for gaps required for entering cabins and safety tolerance intervals. The result is a capacity of 15,000 transported highway vehicles per hour per direction, or 30,000 highway vehicles per hour on a double lane. This corresponds to about 14 freeway lanes. The overall land requirements for track, stations, and storage yards are 3.6 times lower than for the equivalent throughput on a highway. To handle the traffic of one six-lane freeway, Autoshuttle would require only half the highway's space.

In the case of a congested six-lane freeway about to be widened to eight lanes, an Autoshuttle could obviate the expansion. If the Autoshuttle generated substantial demand, its main tracks could be built on the freeway right-of-way, reducing the freeway to four lanes, which would be sufficient because of the lower remaining traffic volumes. The vehicle-carrying capacity would equal that of a 10-lane freeway and could easily be increased. Station location would be flexible because highway vehicles could travel short distances between stations.

This scenario opens the prospect of designing an Autoshuttle in the median of a freeway without needing to widen the cross section of the combined facility at locations with extremely narrow rights-of-way. The loading and unloading capacity of a bay has been estimated on the basis of practical tests of the average time needed to enter a garage with dimensions similar to those of an Autoshuttle

Fig. 2 Passive Switch



cabin. It was estimated that 109 cars or 63 trucks and buses could be loaded per bay per hour. Thus the average station could be quite small, with six loading bays and six unloading bays per direction. This assumes a six-lane freeway with 10 percent of the traffic flow using the entrance. A large station, such as one close to a stadium, would typically have 18 bays per direction and per type, with a total unloading capacity of 4,000 cars per hour. The same value applies to the loading capacity. Cabins could be routed to adjacent stations in cases of excessive demand. The rerouted cars would then drive to the desired exit.

A preliminary survey assessed acceptance of the Autoshuttle concept among 135 people. Given an average fare slightly lower than the vehicle operating cost when driving alone, an average speed close to 112 mph (180 km/h), individualized determination of the destination during the journey, and a daytime convoy frequency of two minutes for cars and six minutes for trucks and buses, the survey asked the question, "Would you use Autoshuttle instead of an ordinary freeway?" Respondents answered yes 95 percent of the time.

The survey showed that if the fare were significantly higher than the vehicle operating cost of driving alone, the decrease in acceptance would be more than proportional to the price increase. Truck operators would even accept a fare higher than the truck operating cost, since labor costs would be lower using Autoshuttle and the faster transportation would directly translate into monetary profit.

An economic study was conducted in Germany for a 35 mi (56 km) sample line between Duisburg and Cologne. According to the lowest prediction, an average of 124,000 highway vehicles per day will travel on this freeway in 2010, the assumed inauguration date of Autoshuttle. If the fare for cars, trucks, and buses were set at a point 15 percent lower than the cost of driving on the freeway for each vehicle type, the line could be privately financed without public subsidy if at least 20 percent of the vehicles switched to Autoshuttle. This value would probably be exceeded.

This analysis has been conducted based on conditions in Germany. In the United States, fuel costs are lower, average vehicle fuel consumption is high, and on many freeways the daily traffic volume is higher than in Germany. All these factors combined yield a minimum changeover rate of the same order of magnitude.

A convenient first application could be U.S. 101 between San Francisco and San Jose, California—a busy 47 mi (76 km) corridor carrying about 200,000 vehicles per day. Autoshuttle would provide reliable transportation between any of the communities along the line. The average fare for cars would be of the order of 15 cents per mile, or $7 for the longest trip. Overall travel time from entering the first station in San Francisco to leaving the last station in San Jose would be 28 minutes. Autoshuttle therefore holds significant promise for a U.S. application as well. The total length of roadways worldwide where Autoshuttle could be built and operated without subsidies and with profit exceeds 60,000 mi (96,500 km).

The technical realization of Autoshuttle is a relatively modest extension of existing maglev technology. The levitation and guidance system has been tested in an experimental setting and the motor has been thoroughly investigated theoretically. The reliability of Autoshuttle is seen to be excellent.

This proposed new transportation concept is capable of mitigating the problems caused by heavy road traffic. Autoshuttle permits the use of conventional highway vehicles and is very safe thanks to the effective derailment protection of the maglev configuration and the modern safety and control system. It is generally the fastest and easiest means of door-to-door transportation for distances between 17 and 250 mi (28 and 400 km) for passenger traffic and 14 and 420 mi (22 and 670 km) for freight. Energy consumption, noise, emissions, and land requirements are less than the corresponding values for other proposed systems.

Users will benefit from frequent stations and from an ecologically and economically reasonable traveling speed that comes close to the maximum. In the case of temporary excess demand at one station, users may simply drive to the next station. Cabins will quickly load from behind and unload from the front. In the end, users will experience individualized door-to-door transportation without ever leaving their vehicles. ▼

Andreas Steingröver and Rasmus Krevet are railway signal engineers in Braunschweig, Germany, who work privately on innovative maglev-based transportation concepts. Robert L. Bertini is an assistant professor of civil engineering at Portland State University, in Portland, Oregon.