The Evolution of Transport

FEATURE

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Is magnetic levitation the future of human mobility?

Travel benefits from orientation-fixed points by which to navigate. Our aim is to provide some fixed points derived from a technical analysis of transport systems that enables us to understand past travel and prepare for its future. Along the way, the lunacy of popular ideas such as car pooling, telecommuting, and the revival of traditional railroads will become clear. Instead, we will offer something far more beautiful: a transport system emitting zero pollutants and sparing the surface landscape, while people on average range hundreds of kilometers daily on a system of "green" mobility.

In a spatially inhomogeneous system, living things are much favored by mobility. A couple of billion years ago bacteria were already equipped with rotating flagella, stirred by electric micromotors of the kind physicists call step motors, and even capable of traveling in reverse.

When a sufficient level of oxygen permitted multicellular architecture, mobility was assured with specialized structures, the muscles. Coordination of the distant muscles of an animal requires a central processing unit and fast wires to carry sensory inputs as well as operational orders. Predators develop in every ecosystem, including that of the monocellular organisms. The evolution of the nervous system, thus, responds to the need for management at a distance. The gazelle must be faster than the lion and have the chance to run. Human primacy in the biosphere is tied to the nervous system, and our development shows how much we owe to the necessity of mobility.

Human mobility stems from four basic instincts. These instincts permit analysts to create a simple model for the complex use that humans make of transport.

The first travel instinct is to stick to the budget of time dedicated to mobility (Figure 1). Humans reside in a protected base, be it a cave, a castle, or a high-rise apartment. Like all animals who have a protected base, we carefully measure the time in which we expose ourselves to the dangers of the external world, be they bears or drunken drivers.

The late Yacov Zahavi measured travel time in the 1970s. The results were invariant, about one hour per day, measured over the year and the entire adult population. Recent measures give the same result from Australia to Zambia. California is higher than the U.S. average because Californians spend more time doing other things in their cars, including eating. Interestingly, the travel-time budget was also about one hour 5,000 years ago. Telecommuting fails to save energy or reduce traffic because when we travel fewer minutes to work, we travel equally more minutes to shop or pursue leisure activities.

The second instinct is to return to the lair in the evening. When people depart from the home, the center of the human world, they use the best means of transport. The homing instinct lies at the core of the success of airlines. Airbus Industries found that about 60% of air passengers in Europe do their business and return on the same day, notwithstanding the higher fare. Shuttles operating from New York and Los Angeles carry a similar proportion of day-trippers. Revived and sustained at great cost, the trains between Boston, New York, and

Washington still fail to accommodate a round trip within one day for most travelers. Thus the airlines, barely challenged, extract a high fare between New York and either of the other two cities.

The third instinct is to spend within the travel-money budget. Families everywhere spend about 12–15% of their disposable income for mobility. Zahavi measured the phenomenon 30 years ago, and data recently gathered show the same narrow range.

The fourth instinct originates in the fact that humans are territorial animals. The objective of territorial animals is to have as large a territory as possible within the natural limits of the possibilities to acquire and manage it. Most of human history is a bloody testimony to the instinct to maximize range.

For humans, a large accessible territory means greater liberty in choosing the three points of gravity of our lives: the home, the workplace, and the school. Four-fifths of all travel ends in this ambit.

Interpreting movement

With this framework, we can begin to interpret the world of movement and the geography that forms its substrate. A person traveling by foot covers about 5 km in an hour. With a 1-hour travel budget to go and return home, a pedestrian's territory would have a radius of 2.5 km and, thus, an area of about 20 km^2. We can define this area as the territorial cell of the individual on foot. Topographic maps until about 1800 (and for much of the world today) showed territory that is tiled with cells of about 20 km^2, often with a village at the center.

When a village flourishes and becomes a city, the 20-km^2 territorial cell fills with people. However, its borders are not breached. Numerous examples of belts or walls of ancient cities show that they never exceeded 5 km in diameter. Even imperial Rome was 20 km^2. Vienna started with a small medieval wall, its Ring. Around 1700, after its victory against the Turks, Vienna built a second belt, the Guertel, which had a diameter of 5 km. Pedestrian Venice is elliptical, with a maximum diameter of about 5 km. Ancient Beijing measured 5 × 10 km and thus seems to break the rule. However, close observation shows that Beijing was a double star—two adjacent cities, one Chinese and the other Mongol, separated by a wall with gates.

The travel situation remained the same until about 1800. There were horses, but few in proportion to potential riders. Horses reflected personal wealth, elevated militaries, and plowed fields. They did little for human mobility. Around 1815, Sweden topped the world in horse ownership with about 1 per 6 people, while Great Britain had about 1 per 10 and Belgium about 1 per 16. Most horses worked on farms. In the United States, where hay was inexpensive, the number of horses per capita peaked around 1900 at about 1 horse per 4 people. Compare that with the ratio today of 4 motor vehicles per 5 people.

Diocletian's Rome had about 1 million inhabitants at the beginning of the 4th century. Constantinople, Europe's largest city in 1700, had about 700,000. London, which would become first in population, had only 676,000 in 1750. In 1800, the great networks of roads created by the Romans still served much of Europe for

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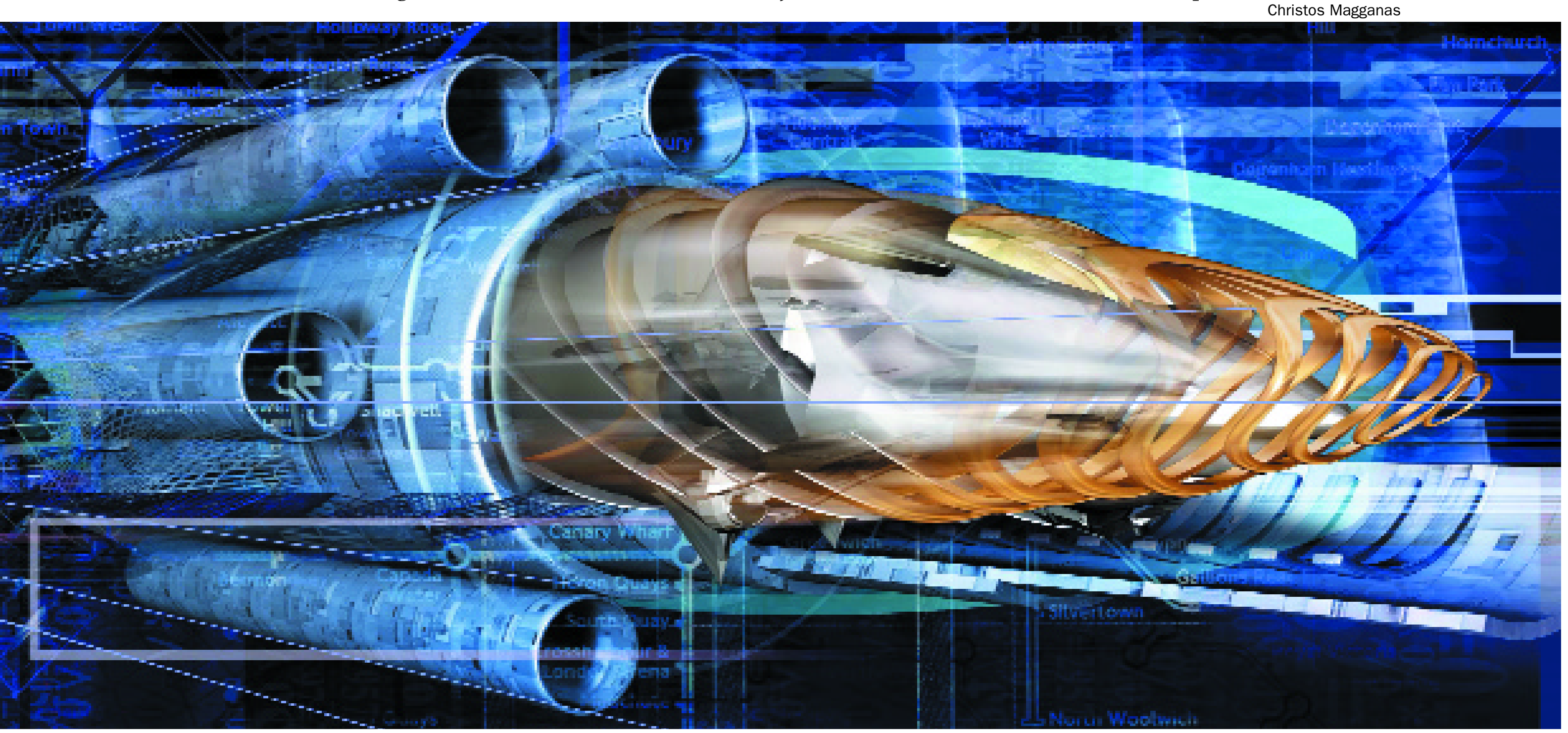

the administrative messengers and the movement of troops and goods. Infantry made up the armies; cavalry were precious and rare.

Mobile machines

Around 1800, new machines for transport entered the field and permitted ever-higher speeds, which revolutionized territorial organization. The highly successful machines are few—train, motor vehicle, and plane—and their diffusion slow. Each has taken from 50 to 100 years to saturate its niche. Each machine carries a progressive evolution of the distance traveled daily that significantly surpasses the 5 km of mobility by foot. Collectively, their outcome is a steady increase in mobility. For example, in the United States, from 1800 to today, mobility has grown an average of 2.7% per year, doubling every 25 years (Figure 2).

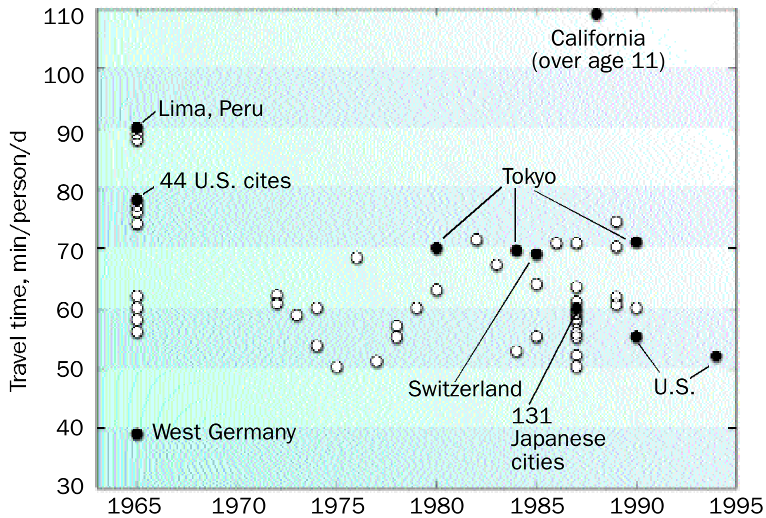

Figure 1. Studies indicate that people all over the world spend about one hour a day traveling. Californians eat, bank, and conduct other activities in their cars. Peruvians travel in unreliable buses from shantytowns to markets and work.

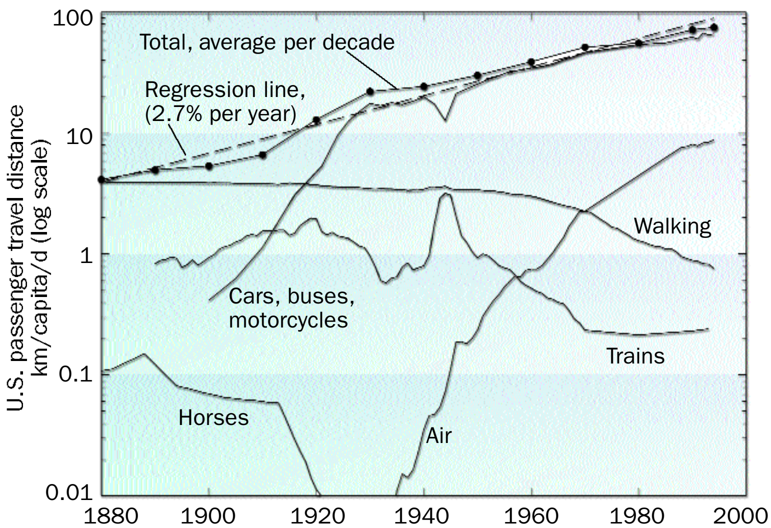

Figure 2. Passenger travel distance per capita per day in the U.S. by all modes shows a decline for horses, walking, and trains; an increase for cars, buses, and motorcyles; and a much more rapid increase for air transportation.

Since about 1920, when General Motors Corp. was formed, the auto has had an average speed in most countries of 35 to 40 km/h, derived by dividing all the kilometers that cars travel by all the hours they travel. Given that 1 h is the daily invariant of the traveler, and that car owners now use their autos for an average of 55 min a day, daily mobility in Europe, for example, is little more than 35 km/day.

The automobile and its mechanical cousins destroyed the village and invented the megalopolis. If the auto gives a mobility of about 35 km/h, then it affords a territory of about 1,000 km^2, 50 times the 20 km^2 of the pedestrian city. Mexico City, based on automobility, officially houses about 30 million people. One can interpolate Mexico City's development to a saturation of about 50 million around 2025. Fifty times the territory equals 50 times the population.

Today, in the developed countries, a motor vehicle stands by for nearly every licensed driver. The mode of transport is saturated. Carmakers can sell more cars, so we each have a second car at our second home or as fashion objects. However, adding cars will not increase our mobility because we have already hit the limit of our travel-time budget. Subways can flourish if they beat the average speed of the car, the 35 km/h door-to-door inclusive travel time. Surface mass transit such as buses, car pooling, and other modes that slow our inclusive travel time get rejected.

Environmentally, the one-license, one-car equation demands that autos on average must be clean. Incremental gains in the efficiency of internal combustion engines will not suffice. The alternative of a world fleet of 1 billion vehicles powered by huge batteries made with poisonous metals such as lead or cadmium poses materials-recycling and disposal problems.

The obvious answer is the zero-pollutant fuel cell, in which compressed hydrogen gas mixes with oxygen from the air to give off electric current in a low-temperature chemical reaction that also makes water. When refiners direct their skills to making hydrogen, its cost should resemble that of gasoline. Moreover, the electrochemical process of the fuel cell is potentially 20–30% more efficient than the thermodynamic process of today's internal combustion engines. Ford and other manufacturers plan to produce 100,000 fuel-cell-powered autos annually within 10 years. Fuel-cell cars will take two to three decades to dominate the fleet because of the large investments in plants required, the 10-year average lifetime of cars, and gradual public acceptance. City air, now fouled mostly by cars, could be pristine by 2050.

Air time

Cars will become cleaner but not faster. The state of technology permits a serious rise in mobility—that is, our average speed—only by augmenting time spent in the air. For all the hoopla about railroads, intercity trains move slowly. A good system, such as Germany's railroad, averages about 65 km/h and peaks at about 95 km/h measured as the distance between terminal points (as the falcon flies). The supreme trains, such as the French TGV, average about 150 km/h. Including the time to reach the station and board, trains are about as speedy as cars but lack the infinite frequency that car owners enjoy.

The mean speed of an airplane is 600 km/h, more than an order of magnitude faster than an auto, and planes are rapidly approaching cars in intercity passenger-kilometers transported. Still, in the United States, daily air time per person is only about 70 s, and Europeans average a scant 20 s daily.

Given that the authors travel on average about 30 min per day on airplanes, huge average increases can clearly occur without harming human health. However, the already inadequate air infrastructures would be violently stressed by a 25-fold rise in traffic in the United States or a 90-fold rise in Europe.

Until recently, the system evolved well by increasing, in proportion to the traffic, the productivity of planes—that is, the number of passenger-kilometers of flight, or the capacity per velocity. By replacing old planes with larger and faster ones, the commercial fleet long remained constant at around 4,000 planes, while passenger-kilometers increased 50-fold. In the past 15 years, however, the builders of airframes have feared to market superjumbo jets, which would cost perhaps $10 billion for the first plane, because of the capital investment. Thus, the airlines make do with smaller craft, and the system has grown abruptly to about 9,000 planes and become horribly congested.

For the currently configured airports, the inevitable growth of high-speed transport will be hard. Looking out to 2050, our objective would be an airport that, without choking, handles 1 million passengers per day—8 to 10 times that of Los Angeles International Airport today. A drastic rethinking of passenger logistics can shrink the

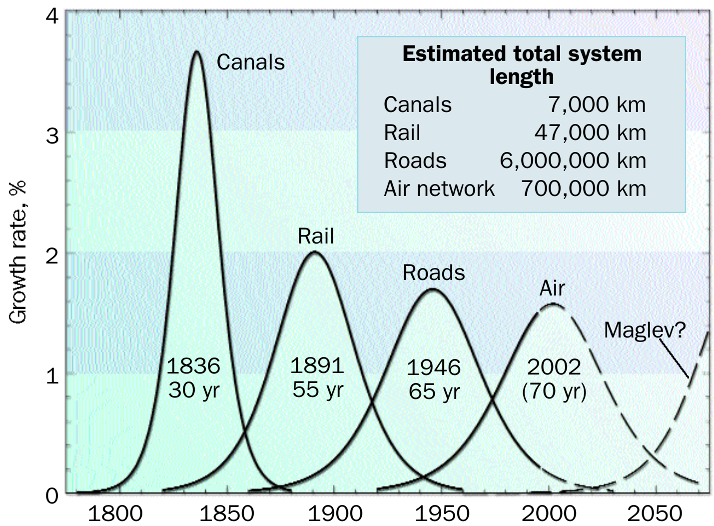

Figure 3. Smoothed historical rates of growth of the major components of the U.S. transport infrastructure, showing the peak year and the time for the system to grow from 10% to 90% of its extent (conjecture shown by dashed curves).

mess. Still, even with more efficient airports, environmental and safety problems loom.

In our outlook, airplanes will consume most of the fuel of the future transport system, a fact of interest to both fuel providers and environmentalists. Kerosene, today's jet fuel, will not pass current environmental tests at future air-traffic volumes. More hydrogen needs to enter the fuel mix, and it will, consistent with the gradual decarbonization of the energy system (see *The Industrial Physicist*, February 2000, pp. 16–19). Still, the transport system clearly needs a high-density mode having the performance characteristic of top airplanes without the problems.

New travel mode

The key is a new kind of transport. In the past 200 years, the system has embraced a new means of transport every 50 years or so: barges, trains, autos, planes (Figure 3). One can view these vehicles and their infrastructures as products competing for market share. The secular evolution is beautiful. Clearly, air will be the big winner for several decades. But the beginning of the millennium must also give birth to a new mode of transport. According to our studies, all bets are on magnetically levitated systems, or maglevs, a "train" with magnetic suspension and propulsion (see *The Industrial Physicist*, December 1998, pp. 12–13).

The maglev is a vehicle without a motor—thus, without combustibles aboard—and without wings and wheels, which is suspended magnetically between two guardrails that resemble an open stator of an electric motor. It is propelled by a magnetic field that, let's say, runs in front and drags it. The maglev is the perfect ana-

log of a bunch of particles in an accelerator.

Hard limits to the possible speed of maglevs do not exist if the maglev runs in an evacuated tunnel, as the Swiss propose for Swissmetro, their future maglev railway system. "Evacuated" means simulating the low pressure that an airplane encounters at 10,000 to 20,000 m of altitude. Tunnels solve the problem of landscape disturbance and can also offer the straight lines that speed needs.

The maglev could break the weight rule—the rule of the ton—that has burdened mobility. The weight of a horse and its gear, a train, an auto, and a jumbo jet at takeoff are all about 1 ton of vehicle per passenger. The maglev could slim the weight to 300 kg, significantly dropping the energy cost of transport.

If room-temperature superconductors succeed, a braking vehicle could also almost totally recover its kinetic energy. The energy consumption of the trains would then basically result from pushing air out of the way. The aerodynamic losses of maglevs running in evacuated tubes, as in the Swiss plan, would decrease with lower air pressure and make the energy efficiency of high-speed transport zoom.

Maglevs offer the best way for electricity to further penetrate transport, the sector from which it has been largely excluded. French railroads, of course, are already powered cleanly and cheaply by nuclear electricity.

Maglev speed

The maglev is similar to a plane that flies low. It can equal the speed of any type of plane, even a hypersonic rocket at 10,000 km/h. Maglevs could accommodate high fluxes of passengers, say 100,000 per hour on a given line. Germans, Japanese, and Americans are studying and experimenting. The transport system calls for it, and we should see a maglev in operation in the next 10 years. Shanghai has just ordered a German system to connect its airport to the city center, a distance of 45 km, and to serve as a test bed for a Shanghai–Beijing line. The U.S. Federal Railroad Administration is currently dangling the plum of construction subsidies for one project in its Maglev Deployment Program.

Will maglevs make us sprawl? This is a legitimate fear. In Europe, since 1950, the tripling of the average speed of travel has extended personal area 10-fold, and so Europe has begun to mimic Los Angeles. The car enlarges the cities but also empties the land. In contrast, maglevs may offer the alternative of a city of separate neighborhoods with fast connections between them.

In cities such as Paris, people live in their quarter and regularly or occasionally travel to other quarters. This behavior suggests a possible form for future human settlements. Quarters could grow around a maglev station with an area of about 1 km^2 and 100,000 inhabitants, be largely pedestrian, and—via the maglev—form part of a network providing most city services within walking distance. The quarters could be surrounded by green land.

Given the maglev's potential, it could be the last in a series of transport technologies, unless we succeed in putting into practice some exotic devilry, such as the disintegrative beaming in *Star Trek*.

Speaking of space, it is amusing to calculate what the maglev might do for the growing demand for transport into that domain. A launch tunnel of a few hundred kilometers and an acceleration less than 1 *g*, which is tolerable to senior citizens, could carry a train of 1,000 tons to orbital velocity (say 25,000 km/h) and launch it into space by a final tunnel ramp, without creating space debris from discarded rocket stages. A train every 5 min could establish a system of transport with destinations around our solar system.

Back down to Earth, let us review our picture of mobility. Speed matters. Humans search for speed because, travel time being fixed, speed gives us territory, that is, access to resources. A person on foot has 20 km^2, a person in a car has 1,000 km^2, and the jet set has a continent. As a rule, the choice is to consume both the travel-budget hour and the disposable money budget, maximizing the distance, that is, the speed.

The 21st century will come to be dominated by the maglev—from the office to the moon, to offer a motto. Consistent with basic instincts, maglevs can serve as the pinnacle of a supersystem for green mobility: cars powered by fuel cells, airplanes powered by hydrogen, and maglevs powered by electricity. Even the bacteria should be impressed with the mobility humans can achieve.

For further reading

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B I O G R A P H Y

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