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In Praise of Diversity

The car has massively transformed physical and cultural aspects of every advanced society. It has enriched our society enormously. It has also cost us heavily and become a victim of its own success. External factors play growing roles. It seems likely that gasoline prices will remain high and that supplies will remain uncertain. Global climate change is becoming serious. So, it’s time to move ahead—to develop transportation systems for the 21st Century. The devastation in New Orleans makes that unfortunate city a good place to start. It’s going to be rebuilt, and that should be done with a view to the next century, not the last.

As often occurs with nonlinear systems, size matters. A system that works at one scale can hurt at another. In the US, with a quarter billion motor vehicles, the adverse side effects from private vehicles have become huge. Worry lists vary. Mine includes dependence on imported oil; supply, vulnerability, and the military costs of oil; global warming; urban sprawl; loss of mobility for the aged, infirm, and poor; and anomie—loss of a sense of community—even for those of us with resources. The intractability of these problems points to the need for new transportation systems.

We don’t yet know what the new systems will look like, but we do know something from history. We understand that the ways in which we’ve embedded the car in society were the result of technological possibility facilitated by the dreams and energies of imaginative people.

The story is complex and nuanced. Henry Ford’s vision of an automobile affordable to every household and the General Motors Futurama at the 1939 World Fair presaged widespread auto ownership and the Interstate highway system. Earlier transport systems such as the trolleys of the early twentieth century came to be seen as outmoded and inflexible, and so were abandoned. Now their successors also seem unsatisfactory. Reinvention will be a social-consensus process involving lots of technology and every aspect of society.

A good way to start is to look at lifestyles we find attractive but which differ from our own. I’m impressed, for example, by the lifestyle of my sister, who lives in Europe and has never owned a car. She lives in a quasi-suburban high-rise building surrounded by lots of public open space. She meets ordinary needs by local shopping and recreation; specialized needs involve short walks to subways that connect everywhere. Her lifestyle appeals to me. Your preferences may differ.

New lifestyles are springing up across America, as cities are being reborn: San Francisco, Washington, Seattle, Philadelphia, Atlanta. Urban renaissance is bringing neighborhood restaurants, entertainment, and specialty shops; “fixer-upper” houses are commanding premium prices from people wanting to experience new-urban amenities. At the same time sprawling suburbs continue to blossom at the metropolitan edge.

Our society is moving simultaneously in many directions: outward and inward; toward low density and toward high density; toward lives based on mobility and lives based on nearby amenities; toward urban renewal and strip-mallization.

In our affluent society, no single lifestyle works for everyone. In turn, diversity in desires compels diversity in transportation systems. The transportation community has suggested all manner of technologies. I heard about dozens of promising ones last summer at the ITS-Davis Conference on transportation and climate change at Asilomar. I hope we experiment with lots of them: automated roadways, high- and low-speed trains, trolleys and buses, independently dispatched services, special services for the infirm, and new ways to organize cities and suburbs. Above all, we need imaginative new systems that will serve diverse lifestyles and exploit diverse technologies, some of which have not yet been invented. That’s to say, we need to encourage a wave of innovation that will carry us to the next stages of development. In turn that will require investment in research and development on a scale we’ve not yet experienced.

It’s time to get moving, and our universities should be leading the way. Reconceptualizing New Orleans’s transport and land use would be a great place to begin. But, wherever and however it happens, the next innovations should create transportation systems that enhance opportunities for diverse populations and for diverse styles of life.

—Paul Craig
Here are 26,000 sensors buried under the pavements of California freeways. Every thirty seconds, those sensors send data to our computers here in Berkeley. The data tell us about the number of cars driving on that freeway and their speed at that time. We also collect, process, and store data about collisions and other incidents. This database, PeMS (Performance Monitoring System), is now by far the most comprehensive source of information about California highways. Today it stores four trillion bytes of information, which are available online at http://pems.eecs.berkeley.edu. We’ve already learned quite a lot from all those data. For example, we’ve found the error in the old belief that an average speed of 40 to 45 mph maximizes traffic capacity; we now know for a fact that maximum capacity occurs at around 60 mph. And we’ve been surprised to discover that some HOV lanes may have the perverse effect of actually adding to congestion.

We’ve learned a lot that’s proving routinely helpful on a day-to-day basis too. We’re pretty sure we can now better manage the flow of traffic and thus lessen congestion. By integrating our research findings into Caltrans’s freeway-management operations, we are helping the state DOT improve traffic behavior.

What else can we learn from PeMS data? Here’s a summary of some of the empirical knowledge about highway congestion we’ve gained from analyzing five year’s worth of PeMS data. There is still much to be learned, and many more ways the data can be analyzed and used by traffic engineers, transportation planners, policymakers, researchers, and the public.

Pravin Varaiya is professor of electrical engineering and computer science at the University of California, Berkeley (varaiya@eecs.berkeley.edu).
Congestion Dynamics

Congestion begins when traffic switches from a 60-mph, high-volume free-flow state to a chaotic, low-speed, low-volume glut of vehicles. The transition occurs when vehicle density (the number of vehicles per mile in a lane) exceeds a critical level. Once it enters the congestion state, it takes a long time for traffic to return to free-flow, and meanwhile delay accumulates. Figure 1 illustrates this phenomenon. It plots speed vs. flow at five-minute intervals across all four lanes of westbound freeway I-10 in Los Angeles. Early in the morning, speed remains at 60 mph while the flow quadruples from 150 vehicles per five-minute segment at 4:00 a.m. to a maximum of 625 vehicles at 5:35 a.m. An influx of vehicles at that point pushes vehicle density above the critical level, forcing traffic into the congestion state. At 9:00 a.m. flow is down to about 500 vehicles per five minutes and speed is much slower at about 30 mph. Traffic doesn’t return to free flow until around 5:00 p.m.

Two important implications follow from speed-flow patterns like that in Figure 1. First, the maximum flow or capacity of a freeway segment is reached while traffic is moving freely. As a result, freeways are most productive when they carry capacity flows at 60 mph; operating freeways at lower speeds always imposes additional delay.

Second, if a ramp metering policy holds back incoming vehicles so that vehicle density is kept below its critical value, traffic will flow freely and congestion will be avoided altogether. Call such a ramp-metering policy an Ideal Metering Policy or IMP. Although IMP may impose queuing delays at on-ramps, there is a net reduction in congestion delay because vehicles on the freeway move at free-flow speeds and at capacity volumes.

**Figure 1**

Speed vs. flow on I-10 westbound in 5 minute intervals from 4:00 am to 6:00 pm

<table>
<thead>
<tr>
<th>Time</th>
<th>Flow</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4:00 am</td>
<td>133 vehicles</td>
<td>67.9 mph</td>
</tr>
<tr>
<td>5:00 pm</td>
<td>530 vehicles</td>
<td>65.1 mph</td>
</tr>
<tr>
<td>5:35 am</td>
<td>607 vehicles</td>
<td>46.9 mph</td>
</tr>
<tr>
<td>9:00 am</td>
<td>493 vehicles</td>
<td>35.2 mph</td>
</tr>
</tbody>
</table>
**BOTTLENECKS**

Bottlenecks may be caused by a physical disruption such as a reduced number of lanes, a change in grade, or an on-ramp with a short merge lane. Such bottlenecks recur predictably at the same time of day and same day of week. Nonrecurring bottlenecks are caused by collisions or highway repairs that block one or more lanes, or by special events like ball games that create demand surges, or by adverse weather that reduces capacity.

We find that nearly half of weekday, peak-period congestion delay in California occurs at 600 recurrent bottlenecks. Taking measures to mitigate the severity of just these bottlenecks would reduce congestion significantly. An additional 28 percent of the peak-period congestion delay is caused by collisions, with 10 percent of it accounting for 90 percent of all collision-induced delay. Rapid detection and clearance of these worst collisions would further reduce congestion.

**RAMP METERING**

As stated above, if traffic were controlled so that vehicle density never exceeds a critical value, congestion could be avoided altogether. Large volume surges at on-ramps can often cause traffic numbers to exceed this critical value. An Ideal Metering Policy (IMP) would prevent these surges and maintain freeway traffic in free-flow state, although at the cost of queuing delay on the ramps. With IMP, freeway traffic flows at capacity, so when demand exceeds capacity, vehicles must queue up. Recall that half of all delay is caused by 600 recurrent bottlenecks. Applying IMP at these bottlenecks alone would yield a net savings in delay equal to 25 percent of all congestion delay. Excess demand would move 21 percent of the congestion delay to on-ramps.

The two pie charts of Figure 2 summarize these estimates. During peak periods, motorists spend twenty percent of their time in congestion. A quarter of this delay could be saved by appropriate ramp metering; collisions cause 28 percent; and excess demand creates 21 percent of total peak-period demand.

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**FIGURE 2**

Total vehicle-hours of travel (left) and sources of congestion (right) during peak periods

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**Bottlenecks**

- Free-flow: 80%
- Congestion: 20%

**Ideal Metering Policy savings**

- 25%

**Excess demand**

- 21%

**Collision**

- 28%

**Other**

- 26%
**TRAVEL-TIME ADVICE**

Congestion increases both average travel time and its uncertainty. Real-time data collected by PeMS can accurately predict travel time and thus reduce uncertainty. Making these predictions available to travelers through websites and telephone services like 511 can provide large benefits, virtually without cost. Accurate predictions can, over time, alter trip patterns in ways that reduce total congestion.

If predictions are available for alternative routes, a traveler can select the one with the shortest predicted travel time. Table 1 lists statistics for five origin-destination pairs in Southern California, each with alternative routes. The shortest route is predicted in two ways. A historical predictor recommends the route that in the past has had the shortest average travel time at the desired time of day. (An experienced commuter would automatically select this route.) A real-time predictor recommends the route that is expected to be shortest based on real-time data, that is, on what is actually happening until this moment. In all five examples, real-time prediction is better than historical prediction. PeMS data can provide real-time estimates with high precision. The column Travel Time Reduction shows how much average travel time improves when using real-time prediction.

Even more significant to travelers is the reduction in travel time uncertainty. We measure this using what we call the ninety percent buffer time, or the amount of time a traveler needs to set aside to be ninety percent sure of reaching the destination on time. As expected, the buffer time is much larger than the average travel time. A real-time predictor achieves large savings in buffer time compared with a historical predictor, as indicated in the last column of Table 1.

**TABLE 1**

Benefits of real-time prediction for peak-period trips between five origin-destination pairs

<table>
<thead>
<tr>
<th>Origin and destination</th>
<th>Number of alternate routes</th>
<th>Average travel time using historical data (minutes)</th>
<th>Travel time reduction using real-time prediction</th>
<th>90% buffer time (minutes)</th>
<th>Buffer time reduction using real-time prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-10 WB, White Ave. to downtown LA</td>
<td>3</td>
<td>41.7</td>
<td>2.9%</td>
<td>75.2</td>
<td>18%</td>
</tr>
<tr>
<td>I-5 SB, Terra Bella St. to downtown LA</td>
<td>2</td>
<td>29.8</td>
<td>17.1%</td>
<td>47.7</td>
<td>31%</td>
</tr>
<tr>
<td>I-15 SB, I-5 to downtown San Diego</td>
<td>2</td>
<td>22.9</td>
<td>8.7%</td>
<td>29.9</td>
<td>20.7%</td>
</tr>
<tr>
<td>I-5 NB, El Toro to Buena Park (I-5 &amp; SR-91)</td>
<td>5</td>
<td>32.9</td>
<td>1.7%</td>
<td>41.8</td>
<td>11%</td>
</tr>
<tr>
<td>I-5 NB, El Toro to Seal Beach (I-405 &amp; SR-22)</td>
<td>2</td>
<td>34.2</td>
<td>4.7%</td>
<td>43.5</td>
<td>7%</td>
</tr>
</tbody>
</table>
HOV Lanes

A high-occupancy-vehicle (HOV) restriction reduces congestion by encouraging carpooling. But it also increases congestion in two ways. First, the restriction imposes a non-HOV congestion penalty by increasing congestion on the non-HOV lanes. Second, it imposes an HOV capacity penalty by decreasing the capacity of the HOV lane itself. Analysis of Bay Area data suggests that the effect of the combined penalties is larger than the positive carpooling effect. Thus, the likely net result of HOV restrictions in the Bay Area is worsening congestion.

Bay Area data facilitate such assessments because the area’s HOV lanes are time limited (5:00 to 9:00 a.m. and 3:00 to 7:00 p.m.), allowing us to compare traffic on the same freeway segments during and outside of HOV restriction periods. Figure 3 helps illustrate the HOV capacity penalty. Like Figure 1, it plots speed vs. flow in lane 1 (the fast lane) in five-minute segments on southbound freeway I-880. The plot on the left is for 4:00 to 7:00 p.m., when this lane is restricted to vehicles with two or more occupants; the plot on the right is for 7:00 to 9:00 p.m., when there is no HOV restriction. The difference between the two behaviors is striking: both record maximum flow of about 145 vehicles per five-minute segment, or 1740 vehicles per hour. But, at this flow, the average speed during HOV restriction is below 50 mph (almost the same as in the non-HOV lanes), whereas the average speed outside HOV-restricted hours is nearly 80 mph.

Another way of viewing this is to observe that the maximum flow at 60 mph during HOV restriction is 110 vehicles per five minutes, while outside HOV restriction times, maximum flow is 140 vehicles per five minutes. That is, HOV restriction at this location leads to a 21 percent capacity penalty. The capacity penalty is imposed because from

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**Figure 3**

Speed vs. flow in lane 1 (HOV lane) for five weekdays in August, 2004 on I-880 southbound

![Graph showing speed vs. flow in HOV lanes](image)
AB 2628, HOV lanes, and Hybrids

California Bill AB 2628, signed into law September 2004, authorizes Caltrans to permit access to HOV lanes by 75,000 single-occupancy hybrid vehicles. However, Caltrans must first gain approval from USDOT, in accordance with the federal transportation bill that just passed Congress. That bill requires Caltrans to limit or discontinue access if the hybrids would degrade HOV operation. According to the federal bill, an HOV lane’s operation is degraded if its speed drops below 45 mph during a peak hour for eighteen days in a consecutive 180-day period. Analysis of available data for the first six months of 2005 shows that every HOV lane in Caltrans districts 4, 5, 11, and 12 already experiences degraded operation. Therefore USDOT would not permit HOV access to single-occupancy hybrids. Caltrans has asked USDOT for a waiver from its requirements.

4:00 to 7:00 p.m. the HOV lane becomes a one-lane highway whose speed is governed by low-speed vehicles—the “snails” out in front. Since the non-HOV lanes are congested, an HOV vehicle wanting to go faster cannot pass a snail in front of it. The number of snails increases as HOV flow increases, causing a steep decline in speed, shown on the left of Figure 3. However, as soon as HOV restriction ends, slower drivers move to the outer lanes, and the fastest drivers move to what was the HOV lane, seen on the right of Figure 3.

Capacity estimates of non-HOV lanes at free-flow are in the range of 2,000–2,200 vehicles/lane/hour. By these estimates HOV lanes in the Bay Area are underutilized, because the number of HOVs using the lanes is on the order of 1,600 vehicles/hour, as we see in Figure 3 and from data for other HOV lanes in the Bay Area. This creates an interest in utilizing the excess capacity by converting HOV lanes to HOT (High Occupancy/Toll) lanes. However, if we take the HOV capacity penalty into account, there is very little room for additional traffic, so even cautious estimates for revenue enhancement in the Bay Area are overly optimistic. Recent legislation permitting hybrid vehicles into HOV lanes will almost certainly increase congestion.

The non-HOV congestion penalty can be illustrated with the help of Figure 4, which compares flows and speeds in left-most lanes 1 and 2 at the same location as in Figure 3. Until 3 p.m., before the HOV restriction begins, the two lanes have the same flow and approximately the same speed. When the HOV restriction begins at 3 p.m., flow in lane 1—now the HOV lane—drops dramatically, and lane 2 flow increases by the same amount. Lane 2 enters the congestion state at 3:45 p.m. with the characteristic rapid decline in flow and speed. The congestion state is caused in part by the non-HOV congestion penalty and in part by excess demand. Observe the steady decline in HOV lane speed from 4:00 to 6:30 p.m. (lower chart) because of the HOV capacity penalty. When the HOV restriction is lifted at 7:00 p.m., speed in both lanes increases dramatically: the snails move to the rightmost lanes and the faster vehicles move to the left lanes.

From evidence of the kind shown in Figures 3 and 4 one may confidently conclude that HOV restrictions in the Bay Area reduce total vehicle-miles traveled, increase congestion delay for non-HOV vehicles, and reduce congestion delay for HOV vehicles. To determine whether the total congestion delay is increased or reduced, we would need to know the average vehicle occupancy in HOV and non-HOV lanes at different times of day. Unfortunately occupancy estimates for the Bay Area vary significantly. Estimates at one extreme imply that HOV restrictions reduce the total number of person-miles traveled; estimates at the other extreme imply HOV lanes slightly increase this number.
CONCLUSION

Congestion consumes twenty percent of the time people spend on California freeways during peak periods. Congestion will increase by ten percent per year, if we assume that travel demand will grow at a rate of two percent in the absence of effective congestion mitigation measures. Designing such measures requires a quantitative understanding of the contribution of the different causes of congestion. This review has summarized the ways that PeMS data are used now to study congestion from different perspectives, ranging from identification of bottlenecks to evaluating the benefits of ramp metering and the effectiveness of HOV lanes. Each study measures the severity of congestion and suggests approaches to its mitigation.

FURTHER READING

Chao Chen and Pravin Varaiya, "Max Flow in D12 Occurs at 60 mph, October 2001; Maximum Throughput in LA Occurs at 60 mph, January 2001," http://pems.eecs.berkeley.edu


The Transition to Hydrogen

BY JOAN OGDEN

Of all alternatives to gasoline fuels, hydrogen offers the greatest long-term potential to radically reduce many problems inherent in transportation fuel use. For example, hydrogen could enhance energy security and reduce dependence on imported oil, since it can be made from various primary energy sources, including natural gas, coal, biomass, and wastes, and from solar, wind, hydro, geothermal, and nuclear energy. Also, hydrogen vehicles have zero tailpipe emissions and are very efficient. If it is made from renewable sources, nuclear power, or fossil sources with carbon emissions captured and sequestered, hydrogen use on a global scale could produce nearly zero greenhouse gas emissions and greatly reduce emissions of air pollutants.

Joan Ogden is associate professor of environmental science and policy and associate policy analyst at the Institute for Transportation Studies at the University of California, Davis (jmogden@ucdavis.edu).
FUEL OF THE FUTURE

Most analysts believe that hydrogen will become a major fuel only if it has very strong support from aggressive public policy aimed at solving these larger problems of energy security and pollution. On the other hand, some suggest that hydrogen and the fuel cells that use it to produce electricity could make possible other developments—such as clean, quiet, mobile electricity generation—that would make them attractive to consumers, and therefore marketable, even without aggressive policy support. Some call hydrogen and fuel cells “disruptive technologies” because they could change how we produce and use energy in profound ways.

But hydrogen also poses the greatest challenges of any alternative fuel. Complex technical, economic, and infrastructure problems must be resolved before it can be used on a large scale. Refining and chemical industries already produce, store, and distribute hydrogen, but the technologies they use need to be adapted for wider use. Building a new hydrogen distribution infrastructure will be expensive and complicated and require solutions to complex logistical problems such as matching supply and demand during a transition. Today, about 95 percent of hydrogen is made from fossil fuels, so although it’s a “clean” fuel when used, its manufacture produces emissions. To realize hydrogen’s benefits fully, production methods that produce no emissions are needed. And although fuel cells and zero-emission hydrogen production systems are progressing rapidly, technical and cost issues must be resolved before they can compete with current fuel technologies.

There remain many questions surrounding a transition to hydrogen. How soon will markets for hydrogen vehicles develop? How will the hydrogen be produced? How will society benefit? How much will it cost to build a hydrogen infrastructure? How soon could hydrogen make a difference in energy use, greenhouse gas emissions, and pollution?

Perhaps the most important question is: what should we do now? Hydrogen has great long-term promise, but implementation will take time and is surrounded by uncertainties. I want to discuss transition issues and their large uncertainties, then suggest near- to mid-term “no-regrets” actions we can take now. ➢
DEMAND

It is not possible to predict future hydrogen demand accurately. Performance and cost of hydrogen vehicles versus competitors is uncertain, as is the future policy landscape. Figure 1 shows four scenarios developed by the USDOE, wherein the market fraction of hydrogen projected for 2050 ranges from 1 percent to 100 percent.

Hydrogen vehicles will not become a commercial product for at least five to ten years. Once they are introduced, it will take time to capture market share and for the existing fleet to retire. Even under the most aggressive scenario, it is unlikely that hydrogen vehicles will constitute more than a few percent of the total fleet by 2025. However, the portion could grow rapidly beyond then. How will we meet this future demand?

Supply

Hydrogen is the most common element in the universe, but on earth it is bound up in chemical compounds such as water (H_2O) or hydrocarbons (fossil fuels or plants). It takes equipment and energy to extract hydrogen from these sources. Hydrogen can be made by electrolysis, which uses electricity to split water molecules into hydrogen and oxygen, or by thermochemical methods that use heat to break down hydrocarbons and separate the hydrogen. Hydrogen can then be stored as a compressed gas at high pressure or as a super-cold liquid (at –253 C), both of which pose infrastructure challenges in terms of storage and delivery to consumers. Hydrogen can be burned in special engines or used in fuel cells, which combine hydrogen and oxygen to produce electricity.

The environmental or energy security benefits we might achieve by using hydrogen vary depending on which primary source produces it and which production method is used. Every stage from well to wheels—from extracting primary resources through manufacturing, distributing, and using a fuel—can produce emissions, and all emissions must be taken into account when adding up the benefits of hydrogen or any fuel. Figure 2 compares well-to-wheels greenhouse gas (GHG) emissions for several alternative-fuel vehicles, including hydrogen from various sources.
**First Steps: Hydrogen Supply During a Transition**

Currently, most hydrogen in the United States is made from natural gas, which is generally cheaper than other sources. It is widely seen as the most likely choice for a transitional source of hydrogen production in the United States in the next few decades. Hydrogen from natural gas has a modest well-to-wheels GHG benefit compared to liquid fossil fuels in improved internal combustion engine (ICE) hybrid electric vehicles. Using natural-gas hydrogen would also reduce air pollutant emissions and oil use, although expanded natural gas use in the United States might eventually require importing it, bringing new security issues. However, over the next decade or so there wouldn’t be enough hydrogen vehicles to have more than a small effect on the US natural gas supply. Even under the most optimistic hydrogen-demand scenarios, natural gas use would increase only a few percent by 2025.

**Future Resource Issues**

It is imperative to develop hydrogen sources that produce very low GHG emissions. Renewables, fossil fuel combined with carbon sequestration, and nuclear energy are all possible sources and can be widely available. But challenges face each of these zero-emission hydrogen supply pathways.

For renewables, the issue is primarily cost rather than technical feasibility. Electrolyzers using solar, wind, hydro, or geothermal power could be built today, but, in the United States, the resulting hydrogen would generally cost more than current methods using natural gas. To derive hydrogen from biomass, very large areas of land are necessary to grow enough feedstock, and competition from the electricity sector for low-cost biomass could drive up prices and further limit availability.

Hydrogen made with nuclear energy can be expensive, unless cheaper off-peak power is used. Thermochemical water-splitting systems powered by nuclear heat are still in the laboratory stage and a number of technical issues must be resolved before they can be built. Also, nuclear hydrogen would have the same waste disposal and proliferation issues as nuclear electricity. ➢

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**Figure 2**

Well-to-wheels greenhouse gas emissions: percentage change from advanced gasoline internal combustion electric vehicles (ICEVs)
Producing hydrogen from fossil sources (coal) using carbon capture and sequestration is receiving considerable attention worldwide as a way of making fuel from coal with near-zero GHG emissions. (With sequestration, carbon is “captured” chemically during hydrogen production and injected into deep underground geological reservoirs for permanent storage.) This approach holds the promise of nearly zero emissions and relatively low cost, assuming that close, suitable carbon disposal sites are available and that hydrogen is produced on a large scale. However, much remains unknown about the potential environmental impacts and feasibility of this method.

There are ample primary resources for hydrogen production in the United States and in most areas of the world. Figure 3 shows primary energy requirements to fuel 100 million hydrogen vehicles (about half the number of light duty vehicles in the United States today), assuming these vehicles are two to three times as efficient as today’s twenty- to thirty-mile-per-gallon gasoline vehicles. There are clearly many resources that could contribute to hydrogen production in the United States in the near term and the long term, including renewable resources and fossil resources with carbon sequestration. Diverse resources might be used in a future hydrogen system (similar to today’s electricity supply), so envisioning the evolution of a future hydrogen supply infrastructure is complex and regionally specific.

### FIGURE 3
Percent of current US use to make enough hydrogen to meet demand

<table>
<thead>
<tr>
<th>Model</th>
<th>Natural gas</th>
<th>Coal</th>
<th>Wind</th>
<th>Bio*</th>
</tr>
</thead>
<tbody>
<tr>
<td>President’s H₂ initiative (100% of fleet)</td>
<td>68%</td>
<td>92%</td>
<td>45%</td>
<td>33%</td>
</tr>
<tr>
<td>2050 study (50% of fleet)</td>
<td>34%</td>
<td>46%</td>
<td>22%</td>
<td>16%</td>
</tr>
<tr>
<td>PNGV (21% of fleet)</td>
<td>14%</td>
<td>18%</td>
<td>9%</td>
<td>7%</td>
</tr>
</tbody>
</table>

* percent of current range + pasture

### COSTS AND TIMELINES

A mature hydrogen refueling infrastructure might cost several hundred to several thousand dollars per vehicle served, depending on the type of supply. Near-term costs would be higher, but they would decrease with experience and as the number of hydrogen vehicles increased. Shell Oil Company recently estimated that an initial nationwide network of 11,000 hydrogen stations in cities and along interstate highways would cost about $12 billion. Full implementation in the US (serving 100 million hydrogen vehicles) might cost hundreds of billions of dollars over a period of several decades. Although these are huge costs, they are of the same order of magnitude as the investment costs of expanding and maintaining the infrastructure for conventional transportation fuels. In other words, we’d have to spend this much anyway.

Once a hydrogen infrastructure is well established, the delivered cost of hydrogen at the pump is likely to be $2.50 to $4 per kilogram ($1/kg hydrogen is comparable to $1/gallon gasoline). Given that hydrogen vehicles might be two to three times as efficient as today’s gasoline cars, the fuel cost per mile could turn out to be less than for current gasoline vehicles.
Even under a scenario of technical success and strong policy, it will be ten to fifteen years before hydrogen energy technologies enter mass markets. Most analysts do not see hydrogen playing a major role in reducing emissions or oil use for several decades. (Local benefits might be felt before this, if hydrogen is used in fleet vehicles in cities, for example.) After 2025, however, hydrogen could help greatly reduce emissions and oil use.

The Debate About Hydrogen: What Now?

There is relatively little dispute that hydrogen is one of very few long-term fuel options that allow radical reductions in greenhouse gases, air pollutants, and oil use. However, there is considerable debate about near-term priorities. Some analysts assert that current support for hydrogen hurts other efforts to reduce carbon emissions in the near term by diverting resources away from them. Is pursuing a long-term option that will not make much difference before 2025 a good strategy? Couldn’t focusing on improved energy efficient technologies, such as gasoline hybrids, solve problems now?

Many effective approaches (such as higher efficiency vehicles), should be pursued simultaneously, both to address energy-related problems in the near term and to drive a long-term shift towards low-carbon fuels such as hydrogen. Policies that encourage energy efficiency need not compete with RD&D (Research, Development, and Demonstration) on hydrogen; indeed, the two parallel efforts complement each other. Many of the technologies needed for hybrid vehicles will also be used in fuel cell vehicles. Low-carbon technologies such as wind power, biomass, or carbon sequestration being developed for the electricity sector could be important for hydrogen as well.

A comprehensive approach should include both, as near-term and long-term strategies. Relying exclusively on vehicle energy efficiency to bring down carbon emissions will not be enough in the long run. Even with efficiency improvements, the growing number of vehicles alone will increase carbon emissions from transportation unless we reduce the carbon content of fuel.

Large-scale use of hydrogen in transportation is not a foregone conclusion, but a vigorous program of hydrogen RD&D is a prudent insurance policy against the need to begin radical decarbonization of other fuels within a few decades, while simultaneously addressing energy security and pollution problems. Given the promise of hydrogen, its long time frame, and its challenges, it is important to provide significant support now, so that hydrogen technologies and strategies will be ready when needed.

A No-Regrets Action Agenda

The following actions can and should be pursued over the next decade or so, and would provide benefits no matter what form the future energy system takes.

Hydrogen-specific actions over the next decade

- Government and industry should offer strong support of RD&D on hydrogen technologies, especially fuel cells, zero-emission hydrogen production (including hydrogen from renewables and research on carbon sequestration), and hydrogen storage.
- Public/private partnerships should bring all stakeholders together to demonstrate hydrogen technologies. The California Fuel Cell Partnership, the US Department of Energy’s FreedomCAR hydrogen program, and the United Nations Development
Program demonstrations of fuel cell buses are examples of efforts already underway, and other regional public/private partnerships are under development worldwide.

- Federal and state governments should use hydrogen technologies in government buildings and vehicle fleets soon—over the next five to ten years.
- Codes and standards for safe hydrogen operation must be established. Thus far, national and international standards organizations, industry representatives, and professional societies have been developing standards with support from the United States and other governments.
- Government, academic, and industry researchers must conduct analyses to better understand external energy costs, energy alternatives, and the role of hydrogen in future energy systems. As noted above, not all hydrogen production methods are equal in terms of greenhouse gases, air pollutants, primary resources, nor implications for security.

**General Actions over the next ten to twenty years**

- Develop consistent national energy policy addressing climate change, air pollution, and national security. Such a policy should outline near-term actions to address these problems now (such as support for energy efficiency and hybrid vehicles), as well as simultaneous actions to develop hydrogen and other technologies that in the long term could produce deep cuts in carbon emissions.
- Conduct RD&D on a wide range of energy-efficient technologies, including hydrogen vehicles, electric drive-train components for hybrid vehicles, and advanced lightweight materials.
- Conduct RD&D on clean-energy technologies with applications in both electricity and hydrogen production, including wind, solar, and gasification technologies, carbon sequestration, and biomass energy.

**CONCLUSION**

Hydrogen has the potential to become an important part of a future transportation system with diverse supply and low emissions. A consistent federal energy policy is urgently needed to enable a progression of clean transportation technologies, starting with efficiency and hybrids now, and moving toward efficient use of low carbon fuels like hydrogen in the longer term. Many of the energy technologies mentioned here are undergoing R&D now, but the overall level of government support for energy R&D is much less than is warranted by the seriousness of the problems, and indeed is much less than other industries such as electronics or pharmaceuticals. Hydrogen is a key option that we should nurture as part of a broader science, technology, and policy initiative.

**FURTHER READING**


The State of California has for many years been at the vanguard of environmental and energy policies, creating strict standards that have afterwards been adopted by other states. Today is no different. Despite a severe budget crunch, California Governor Arnold Schwarzenegger has recommitted the state to a variety of clean energy goals, including deregulation and liberalization of electricity markets, increased energy efficiency in new and retrofit state buildings, and reductions in greenhouse gas emissions. The state has also outlined a major solar-power initiative and a Renewable Portfolio Standard that sets goals for producing electricity from renewable sources. And in pursuit of the elusive zero-emission vehicle—the ZEV—the governor has called for California to take a leading role in advancing the commercialization of hydrogen-powered vehicles with the “California Hydrogen Highway Network.”
In the context of generally progressive energy and environmental policy, and given pressing energy and environmental issues in the state, the effort to advance hydrogen vehicles seems appropriate. However, in the context of severe budget problems and a transportation system that is starved for funding, the California Hydrogen Highway Network could seem an extravagance—whether or not it is a fundamentally good idea. Furthermore, the introduction of a new vehicle type that requires a novel refueling infrastructure is an enormous challenge that will take combined efforts of many stakeholder groups to achieve.

Several key issues confront us in the proposed transition to a hydrogen-powered transportation future. We still do not know how much an entirely new fueling infrastructure would cost, and there is always a risk that we might invest in a new technology that does not catch on as quickly as we expect. Competing technologies—such as hybrid gasoline-electric vehicles (HEVs), “plug-in” HEVs, and advanced battery-powered electric vehicles—continue to improve, and could overshadow hydrogen in the market. Technical issues with hydrogen technologies remain challenging; for example, for hydrogen vehicles to achieve a driving range comparable to conventional vehicles, adequate on-board hydrogen storage is essential, and remains elusive. Driving down costs of fuel cell systems without diminishing durability is proving difficult. New codes and standards
for safety and efficiency have progressed but more work remains. And the critical issue of how to produce hydrogen both economically and with low environmental impacts so that a transition to hydrogen would make sense in the long term is not yet resolved.

The California Hydrogen Blueprint Plan, released in March of 2005, addresses infrastructure and standards development issues. Also, with its staged approach it mitigates some of the concerns about the pace of technological progress and the timing of vehicle commercialization. Let’s take a look at each of these issues and how they are addressed in the Blueprint Plan. But first: a brief history of the California Hydrogen Highway Network.

**The California Hydrogen Highway Network**

On April 20th, 2004, Arnold Schwarzenegger signed the “California Hydrogen Highway Network” Executive Order at a new hydrogen refueling station at UC Davis. Its aim is to stimulate development of hydrogen infrastructure in California, the lack of which is a major barrier to the widespread adoption of hydrogen-powered vehicles. This plan in many ways follows the recommendations for “no-regrets actions” outlined by Joan Ogden earlier in this issue of ACCESS.

The executive order calls for purchase of an increasing number of hydrogen-powered vehicles for use in state vehicle fleets, development of safety standards, building codes, and emergency response procedures for hydrogen fueling stations and vehicles, and incentives to encourage hydrogen vehicle purchase and renewable energy source development. The ultimate goal is to plan and build a substantial hydrogen infrastructure in California by 2010, so that “every Californian will have access to hydrogen fuel, with a significant and increasing percentage produced from clean, renewable sources.”

To help achieve this, the initiative designates the state’s 21 interstate highways as a “California Hydrogen Highway Network” and calls for a plan for transition to a hydrogen economy in California (resulting in the now finalized Blueprint Plan). It also emphasizes negotiations with automakers and fuel cell manufacturers to ensure that hydrogen-powered cars, buses, trucks, and generators become commercially available for California consumers, businesses, and agencies.

The Blueprint Plan lays out a phased approach. Phase 1, from 2005 to 2010, would put in place 50 to 100 hydrogen stations and approximately 2,000 hydrogen-powered vehicles. Phase 2 would increase hydrogen refueling stations to 250, and the number of vehicles to 10,000. Finally, Phase 3 entails expansion of the hydrogen vehicle fleet to 20,000 as the last precursor to full-scale commercialization. The timing of Phases 2 and 3 depends on technological developments and the outcome of biennial reviews.

Initiation of the California Hydrogen Highway Network represents a unique opportunity for alignment of government, industry, and academia to put the state in the forefront of global developments around use of hydrogen and fuel cells. These efforts may be important to both environmental and economic vitality in the state. However, such a dramatic step forward in vehicle technology and energy infrastructure presents huge challenges. It also represents the fascinating intersection of science and technology, human values and behavior, innovation and industry, and politics and government. ➢
As mentioned, several potential pitfalls face California and its plan. Implications of the California Hydrogen Highway Network initiative with regard to these key points are discussed below.

The first of these concerns—infrastructure investment risk—is addressed in the phased Blueprint Plan where initial investments are relatively small. Future and larger investments are contingent on progress of hydrogen-powered vehicle technologies and vehicle commercialization. The Phase 1 plan (through 2010) is estimated to cost the state $53.5 million over five years, or approximately $11 million per year, with an additional $32.5 million contributed by industry for refueling infrastructure. Additional state money will provide incentives to buy hydrogen vehicles and apply the technology to transit buses, shuttle buses, and off-road equipment.

Hydrogen vehicles have considerable associated costs that must be matched by large benefits relative to competing technologies to make them worth the cost of developing. While hydrogen vehicle technology has progressed greatly over the past fifteen years, conventional vehicles have also improved, and HEVs have emerged. Various hybrid-vehicle designs, including "plug-in" hybrids, vehicles running on bio-fuels, and even electric battery vehicles spurred by advances in battery technology are continually raising the bar that hydrogen vehicles much clear in order to justify their costs.

Hydrogen storage remains an important technical hurdle. Achieving a range equivalent to gasoline vehicles in a system that is sufficiently compact and lightweight, safe and quick to refuel, and cost-competitive has remained elusive. Compressed gas storage at...
5,000 psi currently offers practical driving ranges of 100–150 miles for light-duty vehicles without taking up trunk space for a tank, and some new prototypes have achieved up to 250 miles. Ongoing efforts are exploring higher pressure storage at up to 10,000 psi, liquid hydrogen storage, and other solid and liquid forms of storage such as metal hydrides, organic hydrides, and carbon fibers among other options. The Blueprint Plan does not explicitly mandate progress in this area but notes that continued R&D is important.

The costs of hydrogen fuel cell systems have been driven down dramatically in the past fifteen years by improved engineering and design, but remain above cost targets by two to threefold even when projected into high-volume production. Encouraging vehicle production and moving down the learning curve is part of what is necessary to further lower costs, so by stimulating vehicle production the Blueprint Plan may help in this regard. However, the small funding levels proposed do not include additions to basic research on hydrogen and fuel cell technologies currently funded by private industry.

**FIGURE 2**
Recent estimates by the National Research Council of current and future costs of delivered hydrogen by various methods

- Production
- Distribution
- Dispensing
- Carbon Disposal

C = CURRENT
F = FUTURE
and the US Departments of Energy and Defense. More basic R&D is critical to addressing remaining technical challenges, but transportation systems in California have until recently been excluded from major state energy R&D programs, such as the Public Interest Energy Research Program administered by the California Energy Commission.

Codes and standards development for hydrogen and fuel cells has progressed well in recent years, but gaps remain. The Blueprint Plan notes this, highlighting several key areas for prioritization. For example, it calls for an annual review of codes and standards for hydrogen, and designates the State Fire Marshall as the chief responsible agent for hydrogen use in the state.

Environmental concerns about hydrogen stem from the vastly different environmental consequences of possible hydrogen production pathways. Figure 2 compares results from two different models of emissions from hydrogen generation. As the figure shows, hydrogen can virtually eliminate greenhouse gas emissions relative to conventional vehicles if the hydrogen is made from solar or wind electricity or cellulosic ethanol. However, if hydrogen is made from electricity produced from the average mix of sources used today in the US—which is over fifty percent coal—then greenhouse gas emissions would be considerably increased. As Joan Ogden notes, achieving the benefits available from hydrogen ultimately depends on using clean sources of hydrogen production. The Blueprint Plan addresses hydrogen feedstock concerns by recommending that twenty percent of hydrogen production in California be from renewable sources by 2010, in excess of the Statewide Renewable Portfolio Standard goals for the electricity sector, with levels of renewable hydrogen production to increase annually thereafter. The Plan also recommends goals for reducing greenhouse gas emissions and toxic and smog-forming pollutants.

**Key Elements of a California Hydrogen Energy Transition**

The California Hydrogen Blueprint Plan addresses many of the key issues associated with further development of hydrogen infrastructure and vehicles in California. These efforts will need to be coordinated between government, industry, and academia, with cost burdens and risks shared among parties. The Plan outlines a role for “hydrogen energy stations,” which provide electricity as well as hydrogen, but does not heavily emphasize exploring other important early niches for hydrogen production and distribution. These include landfills with methane that can be converted to hydrogen, other sources of “opportunity” fuels that can be obtained with low or no feedstock costs, opportunities to take advantage of existing hydrogen pipelines with excess capacity such as in Torrance, California, opportunities to combine hydrogen production with wind power, and off-road and heavy-duty applications of hydrogen technology. The Blueprint Plan particularly addresses program financing, timing, and the need for additional codes and standards development. It probably underemphasizes the need for service technician training and other education and outreach efforts. The difficulties involved in the transition to hydrogen will likely be as much organizational and institutional as technical. The plan touches on this, but almost certainly underestimates its importance in supporting the large market changes that will clearly be required.
Conclusions

California is home to over 36 million people who drive more than 23 million automobiles. Over 1 million new vehicles are purchased each year in California. By 2010 the population of the state is expected to be nearly forty million, and vehicle miles traveled will increase by nearly seventy billion per year. Hybrid vehicles, biodiesel, and other biofuels are potential means to address some of the energy and pollution problems associated with greater automobile use. However, of known solutions, only cellulosic ethanol, electricity, and hydrogen are capable of significantly and simultaneously addressing greenhouse-gas emission, air pollution, energy security, and oil import concerns. All of these options should be vigorously examined and pursued. However, many automotive and energy companies and leading transportation energy analysts are leaning towards fuel cell or combustion engine vehicles running on hydrogen as the best options for the next dominant design in automobiles.

Furthermore, continued development and deployment of clean-energy technologies are critical to California’s future economic growth, human health and welfare, and environmental quality. Hydrogen technologies represent one important part of this future, but it is essential that efforts to promote hydrogen as an energy carrier occur in the context of a broader clean-energy and energy-efficiency strategy for the state, extending into the electricity and industrial power sectors. The costs of transition to the use of hydrogen beyond niche markets are unlikely to be justified unless the benefits of doing so include clean and sustainable hydrogen production. Clean electricity production is especially important, both to benefit the electricity sector and because much of the energy needed for hydrogen production and/or distribution will be in the form of electricity.

It is therefore essential to expand hydrogen use in the broader context of an overall clean-energy strategy emphasizing renewable energy, energy efficiency, and better operation of existing fuel distribution infrastructures. With the many competing needs for government resources in California, the governor’s hydrogen vision must remain closely tied to the state’s environmental goals if it is to earn public support. This broader focus is necessary to garner the benefits of hydrogen if a hydrogen economy is to develop rapidly; but it will also clearly benefit the state even if progress is slow.

The California Hydrogen Highway Network is an important initiative to advance hydrogen and fuel cell research, development, demonstration, and commercialization. What California does as a worldwide leader in this field over the next decade can have a dramatic impact on global efforts to develop clean energy technologies. Hydrogen’s important limitations and obstacles must be respected, but its tremendous promise leads many of us to look to it as the pathway to break a crippling dependence on imported oil. So far, although the California Hydrogen Highway Network has set ambitious goals and timetables, it is deficient in a few key areas, and it has been underfunded by the Legislature for this fiscal year. Achieving program goals will require follow-through for many years into the future, increased traction in the California Legislature, and the steady commitment and participation of California industry, government, academia, and the general public. The landmark year of 2010, as the gateway to “Phase II” of the Hydrogen Highway Plan, is really just a marker post on a much longer journey.

Further Reading


Bogotá, the Andean capital of Colombia and home to some seven million inhabitants, is widely recognized for having mounted one of the most sustainable urban transport programs anywhere. In 2000, the city began operating a high-speed, high-capacity bus system, called TransMilenio, building upon the experience of Curitiba, Brazil’s much-celebrated success with dedicated busways. Bogotá’s leaders went one step further, giving investment priority to pedestrians, followed by bicycle facilities, then public transit, and lastly cars (i.e., inversely to travel speeds).

More than US$1.7 billion has been poured into transport infrastructure and related urban projects in Bogotá in the past decade. The US$180 million Bogotá spent on bikeways alone from 1999 to 2002 was about half the amount the entire United States spends annually on cycling infrastructure. Such outlays might seem out of proportion for a third-world city where half the population lives in poverty. The World Bank has been roundly criticized for past investments in pricey metros that predominantly benefit the professional class, and now the Bank requires transit projects it funds to meet a “poverty alleviation” litmus test. Bogotá bus and bikeway investments would seem to pass such a test, but have they?

Robert Cervero is professor and chair of the Department of City and Regional Planning at the University of California, Berkeley (robertc@berkeley.edu).
**TransMilenio: Too Successful?**

Within two years of being proposed, the TransMilenio bus-rapid transit (BRT) system was up and running, carrying 800,000 daily passengers along a busy 40-kilometer road axis. By mid-2005, the system had expanded to four lines stretching 55 kilometers. Plans call for TransMilenio to eventually blanket the city with some 400 kilometers of dedicated busways, serving 5.5 million passengers per day.

TransMilenio is the brainchild of a succession of progressive and visionary mayors who felt that giving priority to public transport as well as pedestrians and cyclists was essential to relieving “traffic anarchy” and creating a functional, livable, and sustainable city. Mayors, transit managers, and consultants from around the world come to marvel at Bogotá’s transit achievements in hopes of bringing lessons home.

TransMilenio is the gold standard of BRT. Bus lanes sit in boulevard medians, with weather-protected, attractively designed stations every 500 meters or so. Because double lanes enable buses to overtake each other and raised platforms expedite boarding and alighting, the system has a throughput of 36,000 persons per direction per hour, a number that matches many of the world’s metro systems. Presently, around a million passengers ride TransMilenio buses each weekday, four times the ridership of the 28-kilometer Metro rail system in Medellin, Colombia (and achieved at less than one-fifth of its construction costs). Indeed, the most serious problem the system faces is extreme overcrowding. In 2004, near-riots that required military intervention broke out at several stations because jam-packed buses were leaving people stranded. ➤
Station access was carefully planned. Parking is limited to TransMilenio’s end stations. Nearly half of the 62 stations are served by pedestrian overpasses. A phalanx of sidewalks and bikeways feed into most stations, many embellished by attractive landscaping. Some two dozen civic plazas, pocket parks, and recreational facilities lie within a half kilometer of busway stops. These investments have paid off: seventy percent of TransMilenio users reach stations by foot or bicycle.

Within the first year of opening, Transmilenio registered the following impressive numbers: a 32 percent reduction in average travel times by bus, a 93 percent drop in bus accidents, a 98 percent passenger approval rating, and higher property values along the busway corridor (from not only enhanced access but also lower crime rates and noise levels). Eleven percent of TransMilenio riders were former car drivers. By its fifth anniversary in 2005, TransMilenio was credited with a 40 percent drop in air pollution levels and a 32 percent decline in average commuting times, all achieved without operating subsidies.

Because of overcrowding, accidents, and unanticipated problems like busway pavement buckling (partly due to the accelerated construction schedule), as time passed many middle-class “choice” riders stopped taking TransMilenio. The system’s market share of total trips fell from twenty percent in 2002 (two years into operation) to twelve percent in 2004. Surveys reveal that TransMilenio’s overall quality rating flip-flopped from best to worst in comparison to taxis, public bus, minibuses, and private coaches. In 2001, TransMilenio received a score of 4.56 on a 1-5 scale, where 5 is very good and 1 is very bad, highest among the five major public transport modes. By 2004, its average score had fallen to 3.34, lowest among the five modes.
OTHER INNOVATIONS

Bicycle facilities extend well beyond TransMilenio stations. Currently, Bogotá boasts over 250 kilometers of dedicated bicycle paths called ciclorutas. The Dutch-advised long-range plan calls for the figure to double over the next thirty years. Since the mid-1990s, the share of daily trips by cycling has grown from 0.9 percent to 4 percent. A hospitable environment has helped: perched in a flat valley high in the Andes, Bogotá enjoys a mild climate in spite of its equatorial setting. High densities (at 12,000 persons per square kilometer, Bogotá is one of the densest cities in the Western Hemisphere) and mixed land-use patterns also help make cycling attractive. Three quarters of daily trips in the city are less than ten kilometers, and bicycles can often cover that distance faster than cars through the city’s traffic-snarled streets.

To further promote cycling, Bogotá officials have held car-free days on the first Thursday of February since 2000. On Sundays and holidays, the city closes 120 kilometers of main roads for seven hours to create a Ciclovia (“Cycling Way”) for cyclists, skaters, and pedestrians. When weather’s good, as many as a million and a half cyclists hit the streets of Bogotá on Sundays. Bike-friendly initiatives have been matched by car-restricting ones. Through a license tag system, forty percent of cars are banned from central-city streets during peak hours every day. Bollards have been installed throughout the city core to prevent motorists from parking on sidewalks and bikeways. Old street-vendor marketplaces were razed and transformed into bricked and landscaped public squares. Such enhancements were financed partly by canceling a massive planned ring road and pricey underground metro and by selling off the city’s telephone company to a private venture.

HOW HAVE THE POOR FARED?

How can a city in a developing country saddled with guerrilla warfare and known as the kidnap capital of the world justify investing scarce public resources on “amenities” like pedways, bikepaths, and ornate public squares? Aren’t education, health care, sanitation, and food security higher priorities?

Enrique Peñalosa, the “Robert Moses” of Bogotá who as mayor radically transformed the city’s landscape, sees these investments as social equalizers. The poor, he notes, don’t drive; rather they walk, bike, and take transit. And given the city’s well-publicized security woes, Peñalosa felt that Bogotá had to create a more livable and functional city than anywhere in the western Hemisphere, to stop the brain drain and entice foreign capital and investment. Invoking trickle-down theory, the poor, he reasoned, will eventually reap the benefits of economic expansion.

Peñalosa, now an international planning consultant and said to be eying a run for Colombia’s presidency, remarked at a 2002 lecture at UC Berkeley: “A premise of the new city is that we want society to be as egalitarian as possible. For this purpose, quality-of-life distribution is more important than income distribution.” And quality of life, for this mayor, includes “a living environment as free of motor vehicles as possible.” Further, noted Peñalosa, “our goal is not to generate as much income as possible, but to generate as much happiness as possible.” “On the sidewalks or bike lanes,” he added, “the president of the company and the cleaning lady are equals; there is no hierarchy.”

Critics see things differently. The poor, they charge, have borne the costs of past experiments in physical determinism. The replacement of old but active marketplaces ➢
catering to the poor with lavish public squares, some contend, has created an elitist cityscape. Bikeways span the flatlands while many in the hillsides live in squalor. Particularly incongruous is the sight of world-class bikeway facilities on the periphery of the city paralleling rutted unpaved roads and open sewage channels. Disconnected sections of paved bikeways dot outer areas. Some defend this as a social experiment, aimed to imprint bikeways on the rapidly urbanizing periphery and to ingrain a “bicycle consciousness” in the minds of the young and carless.

It’s cause for concern that since the late 1990s, when Bogotá’s spending spree on transport and urban amenities gained momentum, the poor have become worse off. Bogotá’s Gini Coefficient—a method of measuring income inequality—rose from 0.53 in 1996 to 0.58 in 2001 (0 signifies equality of income and 1 denotes wealth is in the hands of a few). Since 2000, the city’s unemployment rate has risen faster than that of the five next largest cities in Colombia. Within Latin America, Bogotá is also slipping, falling from 13th to 16th in an international competitiveness index of the twenty largest Latin American cities.

Critics have seized upon these statistics to demand political change. Bogotá’s current mayor, Luis Garzón, got elected on a platform that pronounced he cared more “about the bicyclist than the bikeway.” The new administration is channeling funds into education, health care, and social programs. The pendulum has swung from investing heavily in physical capital to focusing on human capital.
Bundling Transport and Housing

As in many Latin American cities, Bogotá is dotted with informal housing clusters, some of which snake up the hillsides to hard-to-reach locations. Figure 1 shows the location of informal settlements which in 2001 housed 22 percent of the city’s population on 18 percent of its land area. To date, 375,000 slum residences have been illegally built in 1,433 different claddestinos, or clandestine neighborhoods. Relatively few public services (sewage lines, piped water, paved roads) reach these areas. Because of the peripheral locations and limited availability of public transport (partly because of steep terrains and rutted roads), the average daily commute of claddestino residents was two and a half hours in 2001. Many unskilled workers seeking day jobs are forced to pay multiple fares for informal paratransit connections to the city, consuming as much as fifteen percent of daily wages.

In response to these acute problems, an innovative land-banking/poverty-alleviation program, called Metrovivienda, was introduced in 1999. Under Metrovivienda, the city acquires plots in open agricultural areas at relatively cheap prices, plats and titles the land, and provides public utilities, roads, and open space. Property is sold to developers at higher prices to help cover infrastructure costs with the proviso that average prices be kept under US$8,500 per unit and affordable to families with incomes of US$200 per month. Because families in the lowest income strata are unable to afford even these prices, households that have moved into Metrovivienda units have come from the upper reaches of low-income groups.

To date, three of the four Metrovivienda projects have been built near one of TransMilenio’s terminuses, each between 100 and 120 hectares in size and housing some 8,000 families. By 2010, the program aims to construct 440,000 new houses. Putting housing near stations helps the city’s poor by killing two birds with one stone—i.e., providing improved housing and public transport services. Those moving from peripheral ➢
illegal settlements into transit-served Metrovivienda projects enjoy both legal, serviced housing and better access to the city’s economic hubs. One estimate shows the number of jobs reachable within an hour’s travel time increased by a factor of three for those moving from illegal housing (Figure 1) to legal Metrovivienda projects.

An important aspect of the Metrovivienda program is the acquisition of land well in advance of the arrival of TransMilenio services. Because Metrovivienda officials serve on the board of TransMilenio, they are well aware of strategic plans and timelines for extending dedicated busway services. This has enabled the organization to acquire land before prices are inflated by the arrival of TransMilenio. A recent study found that those residing close to TransMilenio stations pay higher monthly rents: on average, housing prices fell between 6.8 and 9.3 percent for every five minutes’ increase in walking time to a station. Thus, acquiring land in advance has enabled Metrovivienda to keep prices affordable for low-income households. Transportation is also more affordable. Hillside residents use two different public transit services (a feeder and a mainline), paying on average 3,200 pesos a day (US$1.39) roundtrip. TransMilenio’s feeder buses are free, so its riders pay an average of 1,800 pesos (US$0.78) in daily travel costs.

**VIVA BOGOTÁ**

Metrovivienda is an exemplar of accessibility-based planning in a developing country. By coupling affordable housing with affordable transport, Bogotá leaders have improved access to jobs, shops, and services while reducing the joint costs of what often consumes two-thirds of the poor’s income: housing and transport. Whether or not Metrovivienda makes a serious dent in the city’s housing shortages and traffic woes, it is a positive step forward. Over time, it could very well fulfill Peñalosa’s vision and materially improve the distribution of income as well as quality of life in Colombia’s capital.
The study of travel behavior attempts to understand why, when, where, how, and with whom people travel. It then tries to predict how they will travel in the future. Predictions depend on the design and operation of future transportation systems and on changes in population characteristics. Thus, they are useful tools when choosing among alternative designs for future transportation services and sizing facilities to meet future demands.

Models, generally mathematical, are means for representing past and future behaviors. It’s encouraging to view the accomplishments of travel behavior modeling over the last thirty years and to look ahead to future developments. Thirty years ago I was immersed in doctoral studies and my student and faculty colleagues were intensely involved in travel-behavior research. It was a period of great excitement for us. We argued about potential enhancements to our models, knowing that many could not be implemented because of conceptual and computational challenges that were then beyond the profession’s capabilities. This did not stop us from envisioning the possibilities.
The same phenomenon was a daily part of my academic experience during my years on the faculty at Northwestern University. Students, faculty, and practitioners were generating brilliant ideas about model development, but only some could be implemented with then-available methods. The field has come a long way in this time; once-impossible ideas for refining travel behavior models are now used routinely or are being tested for implementation. It’s a testament to the creativity and commitment of numerous researchers and practitioners that many of those early ideas about models have become standard tools of research or practice.

These developments were supported by major conceptual advances in understanding human behavior and by enhanced methods of model formulation and estimation. Current travel behavior models can trace the effects of travel over time and recognize relationships among activities (i.e., multiple stops for different purposes made in one trip from home) and individuals (i.e., interactions among household members). Advanced geographic coding of locations, new simulation methods, and computation efficiency have all contributed to making these improvements possible.

The most advanced—activity-based models—can account for interactions among household members concerning travel purposes, modes, and destinations, as well as temporal effects such as peak-period traffic, and can provide better understanding of the complexity of human travel behavior. Person movements throughout the course of the day are simulated by accounting for traveler responses to changing conditions. Contemporary models reflect the importance of land use changes and incorporate interactions between land use and transportation. Finally, developments in choice modeling, activity-based analysis, dynamic traffic assignment, and land use modeling have been linked and applied in a variety of realistic contexts.

Major research progress has been fueled by the inherent curiosity of researchers and practitioners, each trying to improve understanding of real-world systems and find new ways to represent underlying behavioral relationships in models. Then, too, there has been a demand on the part of both decision-makers and planners to understand the implications of investment and operating decisions. Yet, much still needs to be done to enhance, extend, validate, and integrate developments of the last thirty years. One critical need is to make the models and predictions more understandable to practitioners and the public leaders responsible for financing and implementing new systems.

This will call for sustained efforts to promote further progress in years ahead, including:

- Developing an integrated system of models that builds on advances in knowledge about human decision-making, development patterns, and transportation system operations.
• Developing and applying techniques to evaluate and validate model performance over time. Such validation must take into account historical observations, reasonableness of predictions, and sensitivity to transportation and land use decisions as well as changes in society and the economy.
• Extending data-collection procedures to include detailed measures of transportation system utilization and performance over a range of time for a large sample of households, transport facilities, and land areas during various time periods.
• Developing institutional support at the federal, state, and local levels to provide funding for research, training of transportation planners and engineers, and adoption and use of advanced models in planning departments.
• Developing techniques for summarizing critical measures of effectiveness so that nontechnical citizens and decision makers can understand and interpret the results of analysis.

Meeting these challenges will require considerable financial and intellectual investment. I expect that the continuing curiosity of researchers and practitioners, as well as the desire for improved decision-making support, will provide the resources to make equally impressive contributions to knowledge and to travel modeling over the next thirty years. Those advances in modeling will support improved transportation system design and more efficient investments in transportation facilities, resulting in faster and easier travel for the growing population of the United States and the rest of the world. ♦

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