Future of Transportation Technology

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My talk this morning is about "intelligent vehicle/highway systems technologies." These are microprocessing communications technologies that provide information to drivers or give drivers additional control over their vehicles. The technologies can be divided into three categories: technologies that are strictly on board the vehicle; technologies that are strictly external to the vehicle, but provide useful information to drivers; and a combination of the two.

In the popular press and in meetings of TRB and similar organizations, there has been a sudden explosion of interest in these technologies as a potential means to make more efficient use of current and future roads. It seems to me that the interest has been generated from three perspectives:

1. The technologies hold some promise to help reduce highway congestion.
2. Some of the safety-related technologies, such as radar braking and lateral longitudinal controls for vehicles, may improve highway safety.
3. Real productivity gains may result from these technologies, particularly for commercial vehicle operators.

For state transportation planners, the potential of these technologies for reducing traffic congestion should be of greatest interest, so I will concentrate on that application. Congestion is obviously not a new problem. We had it back in the twenties, in the fifties and we have it today. What has changed, I think, over the last 50 years is our perception of our ability to deal with congestion.

Some data on Alexandria, Virginia, illustrating typical suburban congestion in the Washington, D.C. area, does a good job of explaining why we have not built our way out of congestion. We can look at three trends from 1970 through 1987, the latest data I have for all these points: changes in vehicle registrations, changes in vehicle miles traveled (VMT), and changes in real-dollar (inflation-adjusted) expenditures on roads.

The data show a 70 percent increase in both VMT and registrations but only a 6 percent increase in real dollar expenditures on roads. Not surprisingly, a failure to spend enough to keep up with changes in demand results in increased traffic congestion. Data for 1983 and 1985 from FHWA showing vehicle hours of delay on freeways indicate a 57 percent increase in just two years; preliminary data out for 1987 make the picture look even worse.

What about the future? I have looked ahead to the year 2005, 16 years ahead, and forecasted growth in VMT of about 3 percent a year, which is just about what FHWA is forecasting. I have used a slightly lower growth rate for vehicle registrations. The real question, though, is expenditures on the roads.

According to FHWA, if we fail to make substantial new investments in road capacity, congestion figures will worsen. This can be seen in data that forecasts 2005 figures on the basis of the 1983 and 1985 points I mentioned earlier. Now, some people may think that the FHWA numbers are unduly pessimistic and that we will indeed begin to spend more money on roads and thus avoid these levels of intolerable congestion. Maybe so, but congestion is clearly already a public concern. It has been popularized in the news media, and is getting increasing attention from public policy makers.

The problem for us as planners is what to do about it. My own sense tells me that the public will not learn to live with levels of congestion anywhere near those being forecast for 2000 and beyond, which suggests that we are going to have to figure out how to manage the congestion problem. We will certainly add some additional road capacity, but the expenditure trends I showed you before suggest that we will not add nearly enough.

Consequently, I foresee increasing movement toward restricting the use of roads. We have already seen a proposal for a ban on truck travel on Los Angeles city streets during peak periods, for example. As congestion gets worse, more of these kinds of initiatives will emerge. Another way to deal with the congestion problem is to make more efficient use of our road systems. Efficiency gains can be made through conventional methods such as car pooling, van pooling, and HOV lanes.

It is the technologies that I mentioned earlier, however, that hold real promise for dealing with the congestion problem by making more efficient use of roads. The first category that I mentioned was driver information. Drivers need to know how to get where they want to go. Before road maps became widely available about 1914, chambers of commerce and other organizations erected signs along the road directing people how to get from here to there. One such sign put up by the Auto Club of Southern California showed the route to California. You had to pull off to the side of the road, look at the billboard, and figure out how to get where you were going.

We have obviously come a long way since then. Improvements in microprocessing and communications technology now allow us to provide drivers information that we could not even dream of just 10 years ago.

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In the area of electronic route planning, considerable work is currently being done in Europe using tele-text and video-text. Tele-text is a television-based means of providing textual information. Video-text relies on computer terminals. The sort of traffic information you can get through this kind of system includes a route finder system currently available in the United Kingdom. It enables you to call up a series of screens on a television set that give information on traffic conditions. You can also get detailed instructions on how to get from here to there, if you have an inexpensive printer that hooks up to a digital television or a computer terminal. You can literally print out driving instructions, for example, instructions on how to go from the Transportation and Road Research Laboratory outside London to Hyde Park Corner.

Here in the United States experimental work is underway on the use of tele-text to provide information. The California Department of Transportation (Caltrans), in particular, is working with a company called Tele-Text Communications in San Jose to develop a television-based system, using tele-text, to provide close to real-time information on traffic conditions.

You can also get textual information, some graphics, and, finally, simplified map displays illustrating the exact location of freeway problems and information about expected delays. Although the system is not yet operational, it is the sort of relatively inexpensive technology to consider as you look ahead to the future.

In addition to helping motorists before they start a trip, such a system could also be used to provide information while they are driving down the road. For example, we know that many owner/operators in the trucking business have televisions in their trucks. Obviously, it is not safe for a single driver to watch television while going down the road, but one of two drivers in a team can be looking at the television to get traffic information as they are rolling down the road.

Another way to provide drivers with better information is through radio broadcasting. I think most of you are aware of Highway Advisory Radio. It is a low power A.M. broadcast of recorded messages about traffic conditions that has been fairly widely used here for a long time. It is not a very sophisticated system.

The Europeans have gone much beyond using F.M.-based technology, and they have some sophisticated traffic broadcasting systems already in operation. The ARI system in West Germany, for example, gives drivers periodic updates on traffic conditions. As better sensors are installed in the road, it is getting closer and closer to providing real-time information on traffic conditions.

I am sure you have all seen Highway Advisory Radio signs around airports and other places. This is probably the latest state of the technology in Europe, where it is called Radio Data System (RDS). It is a digital radio broadcasting system, in effect the radio equivalent of tele-text, which uses a digital signal to provide a stream of information that can be displayed in written form or synthesized voice on the radio.

Because RDS radio broadcasts conform to a European standard, a speech chip used in RDS radios will allow a German driver in the United Kingdom to get traffic information in German because he has a German speech synthesizer in his radio. It is a very sophisticated system, and is already being tested and implemented in Europe.

The next step in driver information technologies is what is being called routing advice systems. These are systems which employ routing algorithms on board the vehicle. The driver uses a key pad to address the computer system, giving a destination, and the system gives instructions on how to get there.

The ROGUE system is another experimental approach being developed in the United States and it is representative of our technologies. ROGUE does not use detailed map displays. Instead, it has a simplified graphics display combined with audio prompts that give the driver information on where to turn. These systems can employ synthesized speech as well.

Finally, a variety of navigation technologies is being explored. The earliest one that I am aware of is called the South Pointing Chariot that was used by the Chinese military. The figure on the chariot always points south, so you can use the device to navigate because you always know where south is.

Here in the United States, there has been interest in on-board vehicle navigation technologies for a long time. One patent dates from 1907, another system from the 1930s. The latter is my favorite, combining a shade and guide map all in one. I do not think that anybody ever actually manufactured it, but it is not a bad idea.

We have come a long way since those early patents in terms of technological improvements. We already have available in the marketplace self-contained, on-board vehicle dead reckoning navigation systems. The best example of these is the ETAK Navigator. It is a U.S. product that initially became available in 1985 and is manufactured by a small company in California called Etak. It uses an electronic map display to navigate. General Motors developed the system as licensee for the Etak technology in the United States. With this early version of the system, the driver inserts a cassette tape into the system. The tape, which is just like a regular audio cassette tape, stores a map database. It has a dead reckoning navigation system with a flux gate compass on board the vehicle, so the vehicle knows where it is in terms of latitude and longitude. That location is indicated by the triangular cursor on the electronic map display.

The driver then tells the system where to go. The destination can be a specific street address with number and street; the intersection of two streets; or simply a street name (If the street is in several different communities, the system will ask you which community you want.)

Once a destination has been identified it shows up on the map display as a blinking star. You then simply drive toward the blinking star, and as you drive, the map constantly re-orients itself. It is a straight-up display, so that every time the vehicle turns the corner the map automatically reorients itself around the cursor. You decide which route you are going to take to get to your destination. The system does not tell you how to get there; it simply provides a changing display and you pick the route to drive.

I find it to be a very useful technology. Some people say that it is dangerous to be looking at one of these things, but the alternative is balancing a map—if you do not know where you are going, you are balancing a street map on the steering wheel while trying to drive. That is just as bad or probably worse than looking at one of these displays.

One experimental General Motors display uses color to highlight major arterials. Another uses black and white—the Bosch-Blaupunkt version of ETAK navigator, which has been licensed is now being manufactured in Germany by Bosch. It will be available in Germany starting next month and in the rest of Europe late in the year. Bosch has improved on the original Etak design by replacing the cassette drive for the map database with a CD-ROM, the little compact disk that can be used for music as well as for storing information.

To deal effectively with traffic congestion, drivers need navigation capabilities like routing advice systems or navigation systems, plus real-time information about traffic conditions. So, you combine the ability to navigate with information about what is happening on the road system ahead of you.

The Japanese have done a lot of work in this area; I think that their AMTICS Program is a model for how to approach this whole issue. AMTICS is an acronym for Advanced Mobile Traffic Information and Communications System. I think that the Japanese have approached this subject correctly from an organizational standpoint. They brought industry together with government to address the problem, and they did it quickly.

The project started in 1987. It was aided by the fact that, at least in Tokyo, an extensive and fairly sophisticated traffic monitoring system had already been installed. A police traffic control center collects and then broadcasts real-time information about traffic conditions. AMTICS goes the next step to integrate this traffic information with on-board vehicle navigation. A pilot test was conducted in April 1988, and the system worked very well. Consequently, the Japanese are talking about commercial applications next year.

The AMTICS system has an Etak-type electronic map display unit and uses a CD-ROM for storing information, as in the Bosch version of the ETAK Navigator. It broadcasts to the vehicle, in real time, information about traffic conditions. The other nice thing about the CD-ROM is that not only can it store map data, but it can also be used to store other information as well—tourist information, "electronic yellow pages" with locations of restaurants and hotels, etc.

A General Motors mock-up shows how one of these systems would look with the full-blown AMTICS type system. It will have the electronic map display. Overlayed on the map display in different colors will be indicators of congestion points ahead. The system also has an electronic yellow pages feature; the driver uses the icons at the bottom of the screen to call up information about hotels and restaurants, gas stations, etc.

As I said earlier, AMTICS can be a model for us here in the United States to provide this kind of information to drivers. We are beginning to move in that direction. A small scale experiment will be beginning in California next year. Called the Pathfinder project, it is a cooperative effort among Caltrans, General Motors, and the FHWA. It is not a large experiment in terms of dollars but it will be doing, in effect, what AMTICS does: give drivers electronic maps; broadcast to the vehicles, in real time, information about traffic conditions; and then see what the drivers do.

That is the critical question. Do drivers really use this information? The Pathfinder experiment will, it is hoped, indicate whether drivers do act on the information.

Obviously, much can also be done with traffic control systems. I think most of you probably know more about this subject than I do, so I will move quickly through this section, except for an item at the end.

The original traffic light was erected in Detroit in 1914. At the time it was installed it worked all by itself, because there were no other traffic lights with which to coordinate. Unfortunately, over half the signalized intersections in the United States still work the same way. There is absolutely no coordination of traffic lights, no synchronization at all with adjacent traffic lights, all of which are doing their own thing and contributing to traffic congestion as a result.

So, we can do a lot in terms of timing of lights. We have known how to do fixed-time synchronization with mechanical systems since the 1920s. Increasingly, these systems are becoming computer controlled and they can be taught to adapt over time. The systems can learn about changes in traffic patterns and adjust light timing accordingly. We can also go to real-time control of traffic lights, like the ACOOT system in the United Kingdom, where traffic light timing changes in real time in response to traffic congestion.

As I mentioned at the beginning of this presentation, corridor controls and HOV lanes are also useful traffic management tools. Ideally, however, corridor control technologies and traffic signal technologies should be an integrated package.

The Smart Corridor Project beginning in California next year will try to do just that. The Smart Corridor is an area in Los Angeles. The Santa Monica Freeway runs down the center of that corridor, between Santa Monica and downtown Los Angeles. In addition to the Santa Monica Freeway, a number of large arterial streets run almost parallel to the corridor. Currently, these streets do not carry much traffic. The idea is to use that excess capacity when there is a problem on the freeway. For example, if a truck has blocked the freeway, motorists should be diverted off the freeway and onto one of these parallel arterials. So you use variable message signs and radio broadcasts to alert drivers to a problem ahead. The drivers then detour off the freeway. The driver who has an ETAK Navigator can look at the Navigator to figure out how to get over to Adams or Venice Boulevard or another street. The traffic light timing on those streets would then be changed to produce a longer green light, which increases vehicle through-put. People would be diverted around the problem and then back onto the freeway.

Finally, we have vehicle control technology. Electronic vehicle identification technologies should be of real interest to you because of their increasing use for a variety of purposes, toll collection being one. Radio frequency transponder technology con now be used to collect tolls from vehicles as they roll through toll plazas, without any need to stop. The technology being tested on the San Diego-Coronado Bridge in California works at speeds up to 35 miles an hour. The vehicle is identified, charged a toll against a debit account or a credit card, and then simply rolls right through. Some attention is also being given to this technology in the East, particularly in the New York metropolitan area.

Electronic vehicle identification technologies can also be used to monitor heavy vehicles. The best example of this application is the Heavy Vehicle Electronic License Plate (HELP) project. The HELP project will use automatic vehicle identification technologies—radio frequency transponders—to identify vehicles, to check their permits, to collect fees on the roll, and to weigh in motion. The HELP Project will be ready for a demonstration phase next year, when the technologies will be tested along Interstate 5 from Washington through California and eastward across Interstate 10. The HELP technology is of interest to the trucking industry as well as to regulators because it promises to reduce delays at toll plazas, weigh stations and ports of entries, thereby offering real productivity gains for the trucking industry.

Finally, automatic vehicle identification can be used for road pricing. Such a system was tested in Hong Kong in the mid-1980s. Technologically, it worked fine. The technology is very reliable, and it is not very expensive. Politically, however, there was strong opposition to road pricing, so it was never actually implemented. As congestion gets worse and worse, however, road pricing becomes a more attractive alternative. For example, until the Dutch government fell last month, its transport minister was seriously interested in road pricing, using transponder technology, to deal with traffic congestion in the Netherlands.

Electronic vehicle location technologies are of serious interest to us in the trucking industry. They have some applications for public service vehicles as well, but from a productivity point of view, the trucking industry is really beginning to use these technologies to track vehicles and to communicate with drivers. There is a variety of ways to do it. Some systems combine LORAN C radio navigation technology to locate the vehicle with two-way communications, generally mobile radio, to keep in touch with the vehicle.

The LORAN C location systems have a dispatcher's work stations. The dispatcher views an electronic map display and uses a control console to poll vehicles on the road. The electronic map display shows vehicles as yellow rectangles and the dispatcher can see, in real time, exactly where the vehicles are going. These kinds of systems are being used by taxi services, police departments, and trucking firms. They have some congestion reduction potential as well because if the driver is stuck in traffic, the dispatcher can suggest alternative routes.

The same sort of location and communication can be accomplished using satellite technologies. There are pure satellite systems and there are approaches that combine satellites with LORAN C. The over-the-road trucking industry is very interested in satellite-based systems. One type of equipment used for satellite tracking is the QUALCOMM system. The QUALCOMM is currently the industry leader in satellite tracking and communications for the trucking industry. A device on its right antenna is used to communicate between the vehicle and the satellite. The driver communicates not by voice but by using a keyboard. The system includes the proverbial "black box" and an electronic map display. The map displays are not as detailed as they are with the systems used for local pickup and delivery operations, but most dispatchers do not need to know exactly where their over-the-road trucks are. They need to know generally where they are. The map might display the progress of a vehicle down Interstate 5 in California, or track a variety of trucks in many different locations on a national scale.

In the truck load sector of the trucking business these technologies are becoming very useful for matching available empty trucks with loads that are coming up. Some tremendous productivity gains are to be had with this technology in the trucking business. The same sort of thing can be done using an Etak-type system with communications.

Vehicle control technologies are basically of two types: technologies to aid the driver, and technologies to actually replace the driver. There is a lot of work going on in Europe on radar braking, automatic headway controls, machine vision—all technologies to give the driver an edge in adverse circumstances.

A radar braking van is being experimented with by a company in San Diego, California. I took a ride in such a van, demonstrated at the University of Michigan last fall by the man who developed the system.

The radar braking system first gives the driver an audio prompt that says "look out, look out." If the driver does not respond quickly enough, the vehicle brakes automatically. It was quite an experience to ride in this van because the driver tried to hit telephone poles and other vehicles. It was a scary experience, but it worked.

Technology not only aids drivers, it can get drivers out of the picture altogether. Technology can be used to either automate the roads or automate the vehicle. The Europeans, again, are very interested in automating the roads, taking control of the vehicle away from the driver through an automated road system. So is a group in California, through the PATH Program. The Europeans though, are investing large amounts of money in this. The Europolis Project, which is currently underway, is a $150 million dollar effort to develop automated roads. It may well be 2050, however, before these technologies really become feasible.

I think that a better approach to automating the driving task is automating the vehicle. The one nice thing about automated vehicles as opposed to automated roads is that automated vehicles can be operated on the existing road infrastructure.

Automated vehicles are being experimented with here in the United States by Martin-Marietta, through the Autonomous Land Vehicle (ALV) Program. This is a project being done for the Defense Advanced Research Projects Agency, DARPA. So, it has military applications, but it could conceivably have civilian applications sometime after the year 2000 as well.

The interesting thing about the ALV project is its rapid progress. The effort began in 1984, and the first demonstration of the vehicle was in 1985. At that time the vehicle could go down a straight paved road at 3 kilometers an hour. It could not steer around obstacles, nor detect obstacles. By 1987 however, the vehicle could travel at 20 kilometers an hour. It could go down a winding road. It could detect obstacles if it knew they were something that it should not hit based on its vision. It could go to the destination specified, stop, turn around and come back. That is significant progress in just a few years.

The obvious question is how rapidly this progress will continue. If the capabilities of this vehicle continue to grow at the rate they have, it is conceivable that these kinds of vehicles could be roadworthy sometime after 2000.

The point of all this, then has been to emphasize that there are some promising new technologies available that may be able to help us deal with traffic congestion. They will not solve the problem by themselves. We are going to have to create some additional road capacity. We are going to have to do some other things as well. But these technologies can buy us some time in some cases, and they can help make more efficient use of the road system if they are wisely implemented.

The DOT Appropriations Bill instructed DOT to do a report on intelligent vehicle highway systems, to review what is happening in Europe and Japan and then suggest possible approaches for a national IVHS program here in the United States.

The report, "Discussion Paper on Intelligent Vehicle Highway Systems (IVHS)," was released recently and is available for comment. It is a good summary of IVHS developments to date and raises some important questions about the desirability of a national program to deal with these kinds of technologies. I encourage you to get the report if you are interested in the subject and to comment to DOT on it.

Douglass B. Lee

The scope of technology considered here encompasses applications of computers (often microchips), in conjunction with other engineering and management innovations, to improve highway operations. Technology that might be used in construction, in construction management, or in the planning process (e.g., traffic flow models) is not covered. The purpose is to assess how the various technologies may affect the future production and consumption of highway services.

Table 1 divides these innovations into two major categories, those primarily of a mechanical nature (propulsion and guidance) and those primarily of an operations nature (communications and identification). In many of these applications, the function (e.g., toll collection) has been carried out for a long time, but technological evolution has changed the performance characteristics of available alternatives.

When discussing new technology, it is always tempting to describe the components of the hardware and software and explain how they work. Although such descriptions are helpful and ultimately necessary for implementation, they are distracting from a planning perspective. Thus the table does not say much about the components or particulars of the technology, and gives only a general indication of what function it performs. In many instances several technologies can be used to produce comparable results.

INDIVIDUAL TECHNOLOGIES

Reviewing the technologies one by one, or by groupings of similar technologies, offers some clues as to which ones might

TABLE 1 HIGHWAY AND RELATED TECHNOLOGY

Function	Method/Subfunction	Prospects	Installation	Remarks/Application
		Mechanical		
Engines	Fuel efficiency	H	V	Pollution reduction
	Emissions control & reporting	H	V	Variable regional standards
Propulsion	Alternative fuels	H	B	Enforcement
	Electric vehicles	M	V	Pollution, energy savings
	Magnetic levitation	X	V	Pollution, energy savings
	Electric highways	X	B	Perhaps long term
Guidance	Lane following	X	B	Very long term
	Collision avoidance	X	V	Closer vehicle spacing
	Night vision	X	V	Incident prevention
Speed	Speed controls	X	V	Accident reduction
		X	V	Enforcement, flow control, incident prevention
High speed ground	High speed rail			
Vehicle size	Limited performance vehicle	X	B	Perhaps long term
		X	B	More lanes per pavement width
		Operations		
Traffic flow	Ramp flow control	M	H	Traffic flow improvement
	Signal coordination	M	H	Traffic flow improvement
	Vehicle sensors	M	H	Detectors with system response
	Signal preemption			
	Incident detection	M	B	Priority vehicles
	Incident response	M	H	Maintain capacity
Communication	Cellular phone	H	H	Communications & coordination
	Aid in distress	M	V	Avoid congestion, central control
	Transit security	M	V	Respond to accidents, threats
	Dispatching/coordination	M	V	Increased traffic performance
Navigation	Dead reckoning	H	B	Just-in-time delivery
	Route display	M	V	Reduce wasted travel
	Route guidance	M	V	Reduce wasted travel
Location	Voice communication	X	B	Real-time feedback
	Cordon or checkpoint	M	V	Fleet management
	Coordinate location	M	B	Traffic flow, pricing
Truck weight	Weight charges	H	V	Traffic, fleet mgmt., pricing
	Weight enforcement	H	B	WIM, by road and axle strength
Toll collection	Credit card	H	H	Instrument roads & bridges
	Electronic pass	M	H	Time savings, billings
	Debit (fare) card	H	B	Permit or area license
	Vehicle	H	B	Tolling on the move
	Identification			
Pavement management	Condition sensors	H	B	Followup billing/debiting
		M	H	Report pavement status
Parking management	Cash control	M	B	Reduce lost receipts
	Security	M	B	Reduce stolen vehicles

NOTE: Prospect symbols are: M = marginal impact on traffic or congestion, H = high priority for application, X = currently expensive relative to benefits. Installation symbols are: V = installed in vehicles only, H = installed in highways and other fixed facilities, B = installation involves both guideway and vehicles. WIM = weight in motion.

make potentially significant contributions to improving highway travel. Each technology or function is rated, in the table, as to whether the expected payoffs are high (H), marginal (M), or distant (X). "High" means that the technology is ready, and that the impacts would be large on such problems as congestion and pollution. "Marginal" means that the technology is currently feasible, but that the anticipated impacts appear relatively small on the performance measures of interest. "Distant" means that the technology requires long-term development, and that the impacts may be modest relative to the cost of applying the technology. This rating is derived entirely from the author's judgment, which undoubtedly differs from the conclusions of other observers.

Mechanical Innovations

The significance of innovations that affect only the vehicle, as distinct from those involving both vehicle and highway, is that vehicle manufacturers can market the features without waiting for highways to implement anything. Hence the apparent popularity of such items as heads-up displays, computerized maps with route guidance, and research on collision avoidance systems. Some of these "smart car" features may be attractive to drivers, but they are not likely to do much to reduce congestion or increase vehicle occupancy.

Alternative fuels are getting a lot of exposure as a means for combating air pollution, but the impacts are likely to range from marginal to the substitution of new pollutants. Reduction of air pollution from highway traffic depends mostly on how much fuel is burned and to some extent on how it is burned. Devices that can monitor both factors, adjust operating parameters, and report when queried on the amounts emitted, could be especially useful in creating pricing incentives to improve fuel efficiency and reduce emissions. Without such incentives, fuel changes and combustion technology will probably have only marginal impact.

Long-term mechanical innovations involving both highways and vehicles (such as electronically powered and guided highways) would seem to be among the least promising. These technologies in effect pack vehicles together more densely and shift the pollution to a different source, doing little else; arrayed against these modest impacts are costs that are difficult to estimate, mostly because of their enormous magnitude. Many of these innovations, such as smaller (limited performance) vehicles and automated steering, require sweeping changes to and major replacement of the existing system before benefits result. Electrically powered vehicles might fill a useful niche, but it is a small one at current highway scales and vehicle speeds.

Operations Innovations

With the possible exception of incident response, most traffic engineering measures involving the technology generate small increases in highway capacity without creating incentives to use the available capacity any more efficiently. Some have the primary effect of rearranging congestion. None, for example, shift trips to off-peak periods or increase vehicle occupancy (even HOV lanes, not listed here as "technology," have only modest-to-negligible impacts on occupancy). To the extent that traffic improvements can prevent operating regimes in the "backward bending" portion of the traffic flow curve, they certainly make sense, but they will not relieve vehicle congestion overall.

Several categories of operations innovations, such as communications and tracking, can be implemented on vehicles alone, and seem to be on the verge of widespread adoption on specialized vehicle fleets. Another innovation that is spilling into highway use from applications in other sectors is automated toll collection, which promises to make user charging—no matter how complex—essentially costless to operate. Manually operated toll booths that require vehicles to stop are unnecessary relics, given the technology now available. The innovations have enormous potential for immediate payoff and are sufficiently developed to be risk-free.

COMBINATIONS OF COMPLEMENTARY TECHNOLOGIES

Not covered in the table are combinations of technology applications that are mutually reinforcing, creating a synthesis at a higher level of application than any single item. A few of the most prominent of these synergistic clusters of innovations are described below.

Centralized Control of Goods Movement

By combining automatic vehicle location (AVL) using satellite navigation, on-board satellite communications and computerized tracking and inventory management systems, the control of freight delivery is entering a new phase. The whereabouts of truck fleets will be tracked much more precisely, and electronically identified cargo—such as in containers—will be followed through internodal transfers in real time. Thus the implementation of just-in-time delivery and precise inventory management will be greatly facilitated.

These developments are taking place primarily in the private sector and the military, and do not require the instrumentation of highways in order to be successful. On the one hand, however, these developments provide opportunities for improved highway management; on the other hand, current highway management imposes limitations (for example in congestion and pavement quality) on the performance of the private sector innovations.

Truck Weight Enforcement and Pavement Conservation

With private fleet owners already in the process of instrumenting their trucks for tracking purposes, a parallel effort on the part of highway managers is especially advantageous. Requiring trucks to carry electronic tags for automatic vehicle identification (AVI), combined with roadside interrogators and weigh-in-motion sensors, allows for the monitoring of heavy vehicle traffic to a level that was previously inconceivable. This information can be used for enforcement of vehicle gross weight restrictions, bridge weight restrictions, and driver time-on-the-road restrictions.

Perhaps even more important, heavy vehicles can be charged user fees based directly on the axle loadings *and* the strength of the roads they are riding on. Rates can be set to create strong incentives for heavily loaded trucks to stay on roads strong enough to carry the weight without undue stress on the pavement, and to use more axles when the benefits justify the costs. Such precision in road use fees can now be implemented at relatively modest cost.

Toll Collection and Congestion Management

Automated collection of tolls from passenger vehicles is probably the functional area with the highest potential impact. It is likely to yield large benefits in financing urban and intercity highways, in reducing congestion and increasing vehicle occupancy, and in guiding investment into those facilities for which users demonstrate a clear willingness to pay. Many technologies are now available for this purpose, and they are cheap enough that standardization is not a prerequisite for implementation. We can experiment with a variety of systems, in a variety of contexts, and see which ones work best.

At present, only a few examples of automated toll collection exist beyond exact change machines, and no U.S. highways are priced according to peak versus off peak. Several expressways planned or under construction, however, will use fully automated toll collection, and it is likely that more will follow. The AVI is not necessary for tolling-in-motion, but it provides advantages that will prove essential in the long run. The ease with which the technology can now be applied creates the opportunity for high levels of local autonomy and innovation in the solution of financing and congestion problems.

Other functional areas where new technology will have major impact have not been mentioned, such as traffic signal coordination and overall flow management. The opportunities for improved utilization of existing facilities are so rich that even the most creative current thinking cannot begin to enumerate them all. It is urgent, however, that transportation planners begin testing and using these technologies as soon as possible.