RECOMMENDED CONGESTION MONITORING OPTIONS FOR WSDOT

WA-RD 317.1

Final Phase I Summary Report
September 1994

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16. ABSTRACT

This is a summary of the results of Phase I for this project. It recommends a two-tiered congestion monitoring system for use in the state of Washington. In uncongested areas of the state it recommends use of volume/capacity ratios to estimate congestion levels. For congested roads, travel time measures are recommended. In addition to these measures, additional data items (mode choice, vehicle volumes, average vehicle occupancy, etc.) are also needed to measure congestion.

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Final Phase I Summary Report
Research Project T9233, Task 27
Traffic Congestion Monitoring

RECOMMENDED CONGESTION MONITORING OPTIONS FOR WSDOT

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DISCLAIMER

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PHASE 1 SUMMARY REPORT

This paper summarizes the recommended congestion monitoring system for the state of Washington. The system is designed to meet the needs of the state of Washington, while limiting the resources required to collect the necessary data for the system.

BACKGROUND

Recent state and federal actions have taken place (or are currently taking place) that emphasize the need to improve the monitoring of changes in traffic volume and congestion occurring across the nation. A number of state and federal laws and regulations require the state to monitor the performance of its highway system in greater detail and in new areas. These laws and regulations include federal requirements under the Clean Air Act (CAA) and the Intermodal Surface Transportation and Efficiency Act (ISTEA), as well as state requirements under several different growth management statutes.

In addition to legislative mandates, the WSDOT has a direct interest in monitoring the performance of its own facilities. As a result of escalating costs, lack of land, long- and short-term environmental impacts, and public resistance to new highway construction, the Department is no longer able to construct sufficient new highway capacity to significantly reduce traffic congestion. Instead, the Department must increasingly rely on a variety of techniques to reduce the demand for existing highway capacity and better manage the demand that remains. Such techniques include

- the addition of HOV lanes and ramp metering systems to freeways,
- the creation of coordinated traffic signal networks,
- the optimization of control strategies for existing coordinated networks,

- the implementation of travel demand management programs such as carpool matching programs, telecommuting, and flexible work hours, and
- a variety of other transportation system management programs.

Many of the techniques that the Department is applying are experimental. Other techniques are controversial. In many cases, the results of the implementation of these techniques are not readily obvious. Consequently, the Department is being asked to spend scarce resources on implementation strategies that produce results that are not readily apparent. In the end, without congestion monitoring the Department is unable to make informed decisions about whether to continue these programs or to abandon them in favor of other more productive programs.

At the same time, the Department often does not have the data needed to accurately respond to questions from the state legislature about the expected outcome of resource expenditures. The result is that the legislature makes decisions without adequate information. A good example of this is the Puget Sound HOV lane system. This system has been quite expensive, but its impact on the mobility of people and freight in the urban area is not well understood. The Department lacks the data needed to describe

- whether travel delay has increased or decreased in the region as a whole;
- how specific markets (freight, buses, SOVs, HOVs) have been impacted by the construction and operation of this system and the varying operational strategies (2+ versus 3+ carpool rules) that are used on different facilities;
- how many people have changed travel modes as a result of the HOV lane system; and
- how (if at all) the HOV lane system has changed travel patterns in the urban area.

While several new data collection efforts are underway (vehicle occupancy monitoring, the incident response database, continued expansion of the Northwest Region Surveillance, Control and Driver Information (SC&DI) system), the Department still lacks much of the basic performance information needed for its own decision making process. Therefore, while meeting federal or state reporting requirements is beneficial, the author believes that primary benefit of a congestion monitoring system is that it will help WSDOT better manage the expenditure of funds in congested areas. This management mechanism will result in more cost-effective programs, as well as better political support for the Department and its selected activities.

RECOMMENDED MEASURES OF EFFECTIVENESS (MOE)

The project team recommends that a combination of measures of effectiveness be used in the state's congestion monitoring system. The project team further recommends that in rural or uncongested urban areas, level of service (LOS) be used as the primary MOE for the congestion monitoring system. In congested urban areas (and on other roads that experience significant congestion) the state should employ a direct measure of delay or excessive travel time as the basis for monitoring congestion. These basic measures of congestion must also be supplemented with measures on the total use of those facilities and the occurrence of "external" factors, such as incidents, inclement weather, mode choice, and other variables that have an effect on mobility.

While a variety of variables have been tried for measuring congestion, the most commonly used measure is LOS. LOS, as defined by the 1985 Highway Capacity Guide, is actually an index, computed from several different measures of effectiveness, depending on the type of highway facility being examined. The LOS index is meant to describe perceived traffic conditions in relation to expected levels of facility performance.

While the LOS indices are easily computed and easily understood by most people interested in highway facility performance, LOS has a number of significant drawbacks for use on congested facilities. The two most important drawbacks with LOS are that 1) the current LOS calculations are not sensitive to many of the traffic control measures being implemented around the state (nation) and 2) the LOS process does not allow the measurement or calculation of marginal facility performance changes within LOS categories. (For example, LOS F means stop-and-go traffic, but it does not differentiate between stop-and-go traffic that lasts 15 minutes and that which lasts 8 hours.) A third problem with LOS is that the LOS process is not designed to account for variations in traffic performance over time or under differing conditions. For example, the LOS calculations are not sensitive to variations in traffic volume by season or the impact of the frequency and duration of incidents on a facility.

Still, in uncongested areas (most rural roads, most roads in smaller urban areas, and even some roads in larger urban areas) LOS provides a very cost-effective measure of congestion. LOS can be computed on the basis of relatively little information (usually roadway geometrics and hourly traffic volumes) that can be cost effectively collected by the state or another operating agency. In fact, the WSDOT and most local jurisdictions in the state are already mandated to monitor facility performance as part of the state's growth management concurrency regulations, and LOS appears to be the initial choice for conducting this monitoring.

At better levels of highway performance (LOS A through C), capacity improvements are not necessary and, if made for other reasons, will not significantly improve existing vehicular performance. Consequently, marginal changes in LOS (for example, improvements within a given LOS grade) are not significant to either the decision making process or the environmental review process. Therefore, a more precise measure of facility performance is unnecessary and the expenditure of funds to provide more precise facility performance measurements is likewise unnecessary.

In areas of the state where congestion exists (LOS D or worse), marginal improvements in facility performance need to be monitored to determine the impacts of specific traffic control measures or groups of measures. ("Marginal improvements" are defined in this proposed system as improvements within a given LOS grade or improvements in the number of days that a facility operates one LOS grade higher than its normal condition.) Although detecting these marginal changes is not required by the state growth management legislation, it is important for managing the state's traffic control process, determining which traffic management strategies are successful, identifying strategies that are not providing measurable benefits, and helping the state select among strategies that are providing measurable benefits.

The best MOEs for monitoring these marginal improvements are based on delay or travel time. These MOEs should be collected directly on specific facilities and aggregated to represent larger geographic areas. Use of travel time and delay will require the determination of appropriate "uncongested" travel times for specific facilities (i.e., how fast average speeds should be on a specific signalized arterial) and sufficient monitoring to determine the frequency, duration, and severity of the times when that level of traffic performance is not being met.

The use of travel time and delay as the primary MOEs for congestion monitoring will also facilitate the comparison of different modes of travel. This is because travel time and delay can be readily measured for each travel mode and because travel times can then be compared directly among modes. (Note that having equal travel times does not mean that alternative travel modes are equivalent; however, such a comparison does provide an important, understandable, and meaningful method of directly comparing different modes.) MOEs based on travel time and delay are also recommended by both the current NCHRP project 7-13, *Quantifying Congestion*, and the recently released FHWA rules and regulations for the ISTEA-mandated congestion management system.

Figure 1 illustrates how travel time information could be used to describe the current status of congestion on an urban road section. A series of tables like those in Figure 1 would provide a reasonable description of congestion within an urban area. These tables would directly quantify the impacts of congestion on specific facilities and would allow tracking of congestion over time.

Figure 1. Example Congestion Monitoring Report

Route ______________

From ____________________ To ____________________

	Time From - To	Travel Time Expected	Travel Time Actual (SOV)	Travel Time Actual (HOV)	Average Vehicle Delay (SOV)	Average Vehicle Occupancy	Average Person Delay	Change From Last Year (min)
AM peak								
mid-day[1]								
PM peak								
night								

Total Daily Vehicle Delay (veh-hrs) ____________

Total Daily Person Delay (per-hrs) ____________

	Hourly Volume	Person Volume	Change From Last Year
AM peak			
mid-day[1]			
PM peak			

Total Daily Volume (Vehicles) ________________ Total Daily Person Volume ________________

1 Additional mid-day time periods may be added. The level of temporal detail provided in this report depends on the availability of data and the need for system accuracy. (For example, the shoulders of the peak period will experience different levels of congestion than either the peak or off-peak periods. If data is collected specifically during these periods, the duration and severity of congestion during these time periods will be more accurately defined.

In addition to these basic measures of effectiveness, other data items should be collected as part of the overall congestion monitoring system. These other data items include, but are not limited to the following:

- vehicle occupancy (to determine differences in vehicle delay and person delay);
- facility volume by mode (including the number of persons walking, riding bicycles, driving alone, sharing rides, and taking transit);
- the number, duration, and severity of incidents;
- the presence of construction activities that disrupt normal traffic flow;
- the occurrence of other mitigating events (weather conditions, floods, labor transit strikes, etc.), and
- the presence and geographic extent of implemented traffic control measures.

Other factors external to the These (and additional) data items are necessary to determine other aspects of travel that may impact the mobility of people and goods, may be impacted by traffic control measures, and may take place instead of, or even cause increases or decreases in, vehicular congestion.

RECOMMENDED DATA COLLECTION PROGRAM

The data requirements for the proposed, two-tiered congestion monitoring program vary with the measures of effectiveness chosen. LOS calculations can be computed for most non-congested roads from data that are already being collected for other purposes. The collection of data on expected and actual travel times in congested areas will require additional effort on the part of WSDOT, the state's MPOs, and the other affected agencies and jurisdictions.

As noted above, data items will be needed in addition to the basic vehicular performance information to provide a reliable congestion management decision support system. These other data items are related to the presence and operation of control systems, the occurrence of incidents and other traffic disruptions, travelers' mode choice decisions, and the existence of travel demand management strategies. Without these additional data items WSDOT (and other state and local agencies) will not be able to use a vehicular congestion monitoring program as a valid decision support system for selecting and evaluating congestion relief and mobility enhancement strategies.

The remainder of this section describes the basic data collection process needed for monitoring congestion in the state.

Non-Congested Areas

The majority of data required for computing LOS in non-congested areas is already available on state highways as a result of other data collection efforts. Daily and peak period volume information on state highways is collected and maintained within the TRIPS database. As a result of the ISTEA-mandated Traffic Monitoring System (TMS), the state should have available (on state routes) the majority of the volume information needed to compute LOS with the 1985 Highway Capacity Manual techniques. The data collected with the TMS are also needed for WSDOT and local jurisdictions to comply with the state's growth management legislation concurrency requirements. The level of effort required for TMS data collection is greater than the level of effort WSDOT undertook for traffic data collection during the 1980s, but it is not extraordinarily large.

Off of state highways, the collection of traffic volume data is the responsibility of the agency that operates each road. As a result of this multi-agency responsibility, the availability of data on these roads, and the quality of the data that are available, varies greatly from jurisdiction to jurisdiction. In most cases, as with WSDOT, the resources available for traffic data collection are limited. Thus, many local jurisdictions do not have comprehensive traffic volume information, and additional data collection efforts will be needed from these agencies to meet both growth management and congestion monitoring system requirements.

In some instances for state highways, additional volume counting will be needed to supplement the TMS traffic counts. These additional data collection efforts will be limited to some portable traffic volume counts, with perhaps some turning movement counts at signalized intersections. Again, in uncongested areas, the counts needed for the congestion monitoring system are likely to also be required for growth management monitoring.

For state highways, roadway geometry and most other input requirements for roadway capacity computations are included in TRIPS, although the TRIPS database does not include a specific variable called "capacity." This information allows the computation of LOS.

Congested Areas - Short Term

In the short term only a limited number of methodologies are available for collecting travel time and delay information. In Seattle, WSDOT may be able to use the existing Surveillance, Control, and Driver Information system (SC&DI) to gather travel time and delay information on portions of the freeway system, but for most other roadways, manual data collection will be needed.

In general, travel time studies are less costly than delay studies and cover a wider geographic area, but they provide less detailed information on the specific causes or extent of delay. Given the broad nature of the congestion monitoring program, the ability to cover a wider geographic area for a lower cost will result in the selection of a data collection approach based on travel time over the direct collection of delay information.

Outside of the Seattle SC&DI system, WSDOT can implement three primary methods of travel time data collection at this time: license plate matching based on laptop computers, license plate matching based on voice recording, and floating car surveys. A previous WSDOT research study showed that the laptop-based computer license plate matching is the most cost-effective method for collecting travel time information. (1) Current research being done by WSDOT and by Volpe Transportation Systems Center may soon provide better travel time techniques, but these techniques have not been proven.

The author recommends an approach to collecting travel time information that is based on license plate matching. WSDOT is currently using this procedure for several research efforts in the Seattle metropolitan area, and various district offices have used it successfully on a number of engineering studies.

The author recommends that in the near term, WSDOT and the affected MPOs select a panel of roadway segments in each urban area. This panel should be selected to represent the travel conditions of each urban area and should include all major roadway sections that are currently experiencing routine congestion. In addition, some roadway segments that are currently not experiencing routine congestion should be incorporated in the panel sample. Panel selection for congestion monitoring can be accomplished in the same manner that a panel of sites was selected for vehicle occupancy counts in the Seattle metropolitan area.

Travel time must then be periodically measured on these road segments to determine the extent, severity, and frequency of congestion. To adequately compute these conditions WSDOT or local agencies will have to collect data several times a year at each site. In addition, the data collection efforts should include travel time runs during both peak and midday travel periods. The exact size and scope of these travel time data collection studies can not be defined without further study. However, a limited data collection effort (panel selection and preliminary travel time data collection) completed within the next year should allow WSDOT to meet the compliance goals incorporated in the draft Congestion Management System rules and regulations.

Discussion is needed among the WSDOT, the state's MPOs, and the affected local jurisdictions to determine the agency(s) responsible for performing these data collection activities.

Congested Areas - Long Term

While the use of manual travel time data collection techniques is appropriate for the short term, these techniques are too costly and staff intensive for long-term use. For the long term, the author recommends a system based on IVHS vehicle probes for traffic monitoring data collection. Use of IVHS techniques would allow the collection of facility performance information 24 hours per day, 365 days per year. This data collection process would eliminate the random error component associated with collecting travel times for only limited hours on a limited number of days. This would significantly improve the accuracy of the monitoring program.

A number of approaches to vehicle probes are possible, depending on the IVHS systems deployed for other purposes. The most cost-effective solution for the state would be to use IVHS vehicles and equipment for multiple purposes whenever possible. For example, the same system that is needed to provide vehicle performance information for congestion monitoring could be used to provide information for advanced traveler information systems and advanced traffic management systems.

Vehicles equipped to act as probes could be obtained from a number of sources. For example, if commercial vehicles carried electronic tags designed to indicate their compliance with regulatory requirements (as proposed by the HELP program), these same vehicles could act as vehicle probes in urban areas. A test of this concept has already been successfully completed in Tacoma on Interstate 5.

Seattle's Metro Transit has currently outfitted each of its buses with a GPS-based system to automatically track vehicle location. This system is designed to provide bus location information for security purposes and for on-time performance information. This same bus performance information could be obtained by WSDOT through a computer-to-computer connection with the Metro system. While additional analysis would be necessary to convert the bus performance information into a reliable estimate of roadway performance, automating this conversion would provide WSDOT with arterial and freeway performance information on almost all important arterials in King County, without the need for additional equipment (other than the computer processing hardware).

Another approach to obtaining vehicle probes would be to outfit specific vehicle fleets with electronic transponders. This has already been done to a limited extent with Community Transit buses operating on Interstate 5. These buses were outfitted with vehicle transponders that are scanned by readers, which use the existing vehicle detection loops already located in the pavement. While this technical modification has been done only as part of an ongoing research project, this same technique could be easily expanded as part of a larger monitoring effort.

This same monitoring technique could also be expanded to automobiles by equipping specific vehicle fleets with transponders. The easiest fleets to equip would be city and state owned cars, as permission to equip them is easier to obtain than for private cars, and because fleet cars often have a central storage or maintenance facility that allows easier placement of electronic tags on the vehicles.

However, it is not clear that enough of these vehicles would operate over a sufficiently wide area and during all hours of the day. As a result, other vehicles might have to be equipped with electronic tags. A logical first choice would be to expand the tagged vehicle fleet to include some large private fleets, such as rental cars, package delivery vehicles, or other corporate fleets. Vehicles of city/county employees willing to volunteer for participation in the project might also be equipped. Finally, private vehicles could be tagged if the public was given other innovative reasons such as an automated toll collection system for the state ferry fleet, or a theft detection device.

Regardless of the types of vehicle probes selected, the installation of the equipment needed to operate a data collection system based on vehicle probes would be fairly expensive. The advantage of the probe system is that these expenditures would be primarily capital costs. The operating costs should be fairly moderate, and the staffing requirements would be fairly limited. In addition, the data available from these systems would be collected continually and should be useful for a number of purposes. More specifics on the needs and options of vehicle probe-based systems can be found in the body of the technical report for this project and in the appendix of this summary.

Other Data Collection Items

To complement vehicle performance information, the congestion monitoring system requires other information that describes the mobility of the urban population that chooses not to drive alone and the external causes of congestion. Other data items that need to be collected include, but are not limited to, the following:

- vehicle occupancy (to determine differences in vehicle delay and person delay);
- volume by mode for specific corridors or facilities (including the number of persons walking, riding bicycles, driving alone, sharing rides, and taking transit);
- the number, duration, and severity of incidents;
- the existence, duration, and extent of external factors beyond the control of normal traffic operation controls that effect traffic flow (e.g., construction events, bad weather, and transit strikes), and
- the presence and geographic extent of implemented traffic control measures.

Vehicle occupancy data are needed to quantify any mode shift that results from HOV incentives and carpool programs instituted as part of demand management strategies. Bus ridership information must also be included in the basic vehicle occupancy figures, although this information can be obtained from the local transit authorities. The existing WSDOT vehicle occupancy program in the Seattle metropolitan area is sufficient as a starting point for this effort. Similar data collection programs are needed in the other congested urban areas of the state.

Estimates are also needed on the number of travelers (particularly commuters) using other alternative modes of transportation, including bicycling and walking. These data collection efforts should be performed once per year.

The Department needs a data collection process for incident response information. Because incidents cause such a high proportion of urban congestion, it is important for decision makers to understand the types of incidents that are occurring, how quickly they are being cleared, and the impact they have on congestion. This information is also necessary to provide a more rigorous understanding of both the relative split between incident-caused congestion and routine congestion, and the effectiveness of the incident response tactics the state and local agencies are employing. The database under construction for District 1 appears to meet most of these needs, although a more automated process for obtaining the WSP response information is needed.

The state may also wish to maintain data on extraneous events. For example, the Department may want to collect, store, and use weather information as part of the congestion monitoring system, as the weather can have a significant impact on traffic performance. Much of the information needed for this step can be obtained from existing National Weather Service computers and databases. Data on the timing, extent and location of construction activities would provide the monitoring system with explanations of why certain highway segments performed poorly on specific days or years. The occurrence of transit strikes would also be an "outside" variable that would be useful as an explanatory variable for the monitoring system.

Finally, the state or MPO needs to maintain a complete catalog of the congestion mitigation strategies in place in each urban area, the geographic distribution of those strategies, and the dates of their implementation or effectiveness. This information is needed to allow comparison of the effectiveness of these programs from one geographic area to another.

RECOMMENDED WSDOT ACTIONS

As the preliminary steps toward developing a congestion monitoring system, the author recommends that WSDOT pursues the following actions.

- Create working groups (one per MPO) empowered to develop the congestion monitoring system within their geographic area (there should also be an statewide or state-level "working group" that is responsible for ensuring that the congestion monitoring systems from different urban areas are compatible and can eventually converge to one common system).
- Determine the desired output of the congestion monitoring system and the MOEs the system is expected to produce. (The initial recommendations for this effort are given in this summary.)
- Determine which data are already being collected within each urban area that can be used to meet the needs of the congestion monitoring system.
- Determine the remaining data collection needs and an approximate short-term cost for those needs.
- Determine the funding source that will pay for the data collection efforts.
- Refine the congestion monitoring system data requirements and reporting functions to remain within budgetary constraints.
- Have the MPO working groups select the roadway panel sections on which travel time runs should be collected (assuming the collection of travel time data as recommended above).
- Determine long range plans to collect the data necessary for the planned advanced traveler information and advanced traffic control systems, and for the interaction of these systems with the congestion monitoring system.
- Develop funding for these systems, in coordination with the other projects identified in the statewide IVHS system plan.

- Develop the software and/or procedures necessary for maintaining the congestion monitoring system.

A large portion of this work must be done in close cooperation with state MPOs and local jurisdictions.

The biggest obstacles for the Department will be to determine the funding responsibility for collecting the data not currently being obtained, and then to maintain this data collection effort in an era of tight budgets.

APPENDIX
NEEDS AND OPTIONS FOR VEHICLE PROBE-BASED SYSTEMS

This appendix briefly outlines the requirements for building and operating a data collection system based on vehicle probes. In addition, several options for meeting those needs are presented, and the strengths and weaknesses of each alternative are discussed. Note that for each of these alternatives, a number of vendors are selling specific devices and equipment, and each vendor's equipment may use a different technology (e.g., RF-based versus microwave-based vehicle tags). Thus, within each of the three scenarios described below, a great deal of choice remains regarding the actual design of the system.

As a result of this array of choices, a large number of electronic systems have the potential to allow vehicles to act as probes in the traffic stream. Alternative vehicle probe systems differ in the technologies they use to transmit information to and from the vehicle and in the information they include in the messages that are transmitted. The basic vehicle probe system includes the following components:

- a device (tag) that identifies specific vehicles,
- a procedure for reading the data from the tag at the roadside,
- a procedure for transmitting the data obtained at the roadside to a central location, and
- a processing step in which the data are converted into information that is useful for various applications.

In addition, in some vehicle probe systems, information is transferred from the roadside to the vehicle.

The basic alternative architectures for performing these tasks are presented below.

CONVENTIONAL ONE-WAY TAGS

This system design is pioneered by the Amtech corporation for use in automated toll collection systems. The design consists of a fixed, one-way vehicle tag and roadside readers. Vehicles are equipped with an electronic tag that contains a fixed vehicle identification number. The tag is scanned by a reader antenna located either in the pavement or beside the road.

Information collected by the reader (tag number and time of passage) is stored in a computer at the reader site. From that computer, data are transferred (usually by telephone line or fiber-optic cable) to a central point for processing. The location of the reader antenna indicates the physical location of the vehicle that has been detected and the direction of vehicle travel.

The central computer takes this vehicle location and time information, matches the vehicle sighting with a sighting of that same vehicle from a reader device upstream of the current reader, and computes the time differential between vehicle sightings. Two sightings of the same vehicle are necessary to provide vehicle performance information for the road segment defined by the two readers.

The advantage of this system design is its simplicity. The data read from the vehicle tag are limited and thus more reliable. The vehicle tag is limited in function and thus inexpensive to build. The computation of travel time is very straightforward, as geographic location and time of arrival are both provided by the reader device (although the clocks on all readers/computers in the system must be coordinated), and the communication process is easily defined and built.

The disadvantages of this system are that it requires a large number of readers to provide information for a large geographic area, and it requires reliable, high speed communications to each reader site. Each time the system is expanded to new roads, more readers are required and additional communications are needed. Both of these requirements are expensive. However, once the system has been built, the number of tagged, equipped vehicles can increase significantly without a pronounced change in operating cost.

GPS-BASED SYSTEMS

To get around the communications difficulty of the first alternative, the second alternative uses a global positioning system and either satellite or radio-based communications to determine vehicle location. In this alternative, vehicle tags are associated with a specific X/Y/Z set of coordinates determined by a GPS system every few seconds (or minutes, depending on the system). This information is relayed by satellite (or radio) communications to a central computer.

Once at the central computer, the GPS-based location of each vehicle is matched against known road locations to identify the vehicle position on each road. Traffic performance can be computed on the basis of the relative position of each vehicle from one time interval to another. However, these computations (locating a vehicle on a specific road segment and then determining its movement from one location to the next) are much more complex and processor intensive than the travel time computations in the first alternative, as the GPS-based system is not constrained to specific roads and locations. Thus, this alternative's central processing component is more expensive than the first alternative's.

For communications, GPS-based systems have an advantage in that they do not require the high capital cost associated with placing readers and communications lines around the urban area; however, the GPS receivers can be expensive, and satellite communications have much higher operating expenses than conventional phone lines. Depending on the communications process selected (radio versus satellite versus other processes) "bandwidth" problems may also occur. (That is, different communications media can only transmit so much information at a time. Fiber-optic cable has a very high capacity, while some over-the-air transmission technologies have fairly small capacities.)

By transmitting vehicle position information directly from the vehicles to the central point, this architecture avoids the need for reader devices, but it creates a significant volume of data that must be transferred over the air. Generally, the more capacity the over-the-air broadcast technology has, the more expensive is the transmission of data. Thus, another trade-off occurs. If a large number of vehicles carry tags in this architecture, the transmission cost of getting those data back to the central computer can become expensive. However, limiting the number of vehicles with tags reduces the sample of probes available for use within the system.

Finally, over-the-air transmission of information tends to be charged on a fee-for-service basis. Thus, the more vehicles that are tagged, the greater is the operating cost of the system. For the first alternative, this is not true, as the communications charges (line based) tend to be fixed.

Essentially, for the "reader" based systems, geographic expansion of the system represents additional càpital costs but relatively few additional operating costs. Expansion of the number of tagged vehicles has little or no operating cost impact. For the over-the-air alternative, geographic expansion (within broad limits) has little impact on costs, while expanding the number of tagged vehicles can have a significant impact on the operating cost of the system.

TWO-WAY COMMUNICATIONS

A third system design requires two-directional communications between the vehicles and the roadside. In this alternative, the vehicle tag is more complex than in the first scenario. The vehicle tag stores information on vehicle location and time (passed from the roadside) and computes the travel time between reader locations. This information is then passed back to the reader, which then transmits the information to a central computer.

The advantage of this system is that the processing load of the central computer is substantially reduced in comparison to both the first and second alternatives. However, this alternative suffers from the same communications requirements and costs associated with the first alternative. This system is most applicable if the vehicles acting as probes are equipped with externally linked route guidance devices.

This alternative can also be used as a variation of the second alternative discussed above. In this variation, the GPS system indicates vehicle position, and the on-board electronics compute vehicle performance. This information is then transmitted directly to the central computer via either satellite or other over-the-air communications technologies.

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