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Development and Evaluation of Selected Mobility Applications for VII: Concept of Operations

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Abstract

This report describes the concept of operations for the three mobility applications that PATH is developing and evaluating under the sponsorship of the FHWA Exploratory Advanced Research Program. These applications are intended to use DSRC wireless communications among vehicles and between vehicles and the roadway infrastructure to improve mobility on limited-access highways. The first application combines ramp metering with variable speed limits to enhance control of traffic so that traffic flow breakdowns can be deferred or avoided at bottleneck locations. The second application uses vehicle-vehicle communication to improve the performance of adaptive cruise control systems so that they can operate safely with smaller longitudinal gaps and vehicle-roadside communication to provide adjustments to their set speed and gap settings to adapt to changes in local traffic conditions. The third application uses vehicle-vehicle communication to enable three tractor-trailer trucks to drive in a coordinated platoon at short enough gaps that they can substantially reduce their aerodynamic drag and increase the effective capacity of their lane.

Key Words: active traffic management, variable speed limits, adaptive cruise control, cooperative adaptive cruise control, truck automation, truck platooning, DSRC applications

Vision

The performance of our roadway transportation system has long been limited by the low level of integration between vehicles and the roadway infrastructure, which have traditionally operated almost independently (except for the tire/pavement contact patch). The wireless DSRC data communication system being developed under the Vehicle-Infrastructure Integration (VII) initiative offers an extraordinary opportunity to connect the vehicles and roadway infrastructure (and vehicles with each other) so that they can operate as a truly integrated transportation system. Although such integration has been implemented for a long time in the rail and air transport modes (and to some extent in the marine mode as well), it has been elusive until now in the much larger road transportation system.

The VII initiative has been focused on development of the wireless communication link and its directly related technologies (vehicle positioning and infrastructure-based data handling). Some of the earliest expected applications of the VII technology (called Day One use cases) are also being defined and explored, but there has been little if any attention to the longer-term applications, which have the potential to produce significantly larger improvements in transportation system performance. This project aims to make a large step toward defining several of these key applications and showing their potential contributions to improving mobility by smoothing out disturbances in highway traffic and increasing the capacity per highway lane so that congestion can be mitigated.

The limitations in today's highway capacity and most of the disturbances to the stability of traffic flow are direct consequences of the performance limitations of drivers, combined with limitations in the information available to inform their driving decision making. Drivers are not able to judge their distance or closing rate relative to other vehicles or their position within a lane with the accuracy that modern sensor systems can. Sensors that can measure these variables accurately are still limited by line of sight considerations, and cannot detect traffic conditions with high fidelity at long range. More complete information about both local and regional traffic conditions can only be provided by active communication of data to vehicles.

In addition to their perceptual limitations, drivers also have significant variations in their response times for acceleration, deceleration and turning maneuvers. This limits their ability to control vehicle speed and steering, and requires them to maintain substantial separations relative to other vehicles in order to feel secure and comfortable. Modern highway lanes are twice the width of large passenger cars, and the mean longitudinal separation between vehicles driving at maximum lane capacity (2200 vehicles/hour) at highway speed (60 mph) is about nine car lengths. The combination of these two factors means that the vehicles are only occupying about 4.5% of the roadway infrastructure surface area when the roadway is operating at its maximum throughput (or efficiency). If this percentage can be increased even moderately by use of communication and control technology, the roadway efficiency improvement would be very large.

The drivers' limitations can be overcome through the combination of information and control technology, building on VII technology to:

(a) provide real-time traffic condition information of unprecedented accuracy and completeness, with each vehicle serving as a traffic data probe;
(b) provide customized target speed guidance to vehicles, so that they (or their drivers) can be advised to travel at a speed that will be favorable not only for its own driver but for the flow of all traffic sharing its highway;
(c) enable vehicles to receive detailed real-time driving status information from neighboring vehicles, so that their driving can be closely coordinated to reduce the needed separation and the propagation of disturbances.

The control technology uses the enhanced data to command vehicle movements reliably and accurately, so that shock waves can be minimized and vehicles can drive closer together without sacrificing speed or safety. This means that traffic flow can be smoother and each unit of roadway infrastructure can accommodate a higher traffic volume, improving mobility in two ways.

This project is expected to contribute to future mobility improvements by facilitating the implementation of:

(1) Innovative traffic management strategies that provide real-time speed recommendations to vehicles so that highway traffic flow disturbances can be minimized and attenuated more rapidly and thoroughly than today;
(2) Traffic-responsive cooperative adaptive cruise control systems that can increase the throughput capacity per lane while providing drivers with smooth, comfortable and reassuring driving performance;
(3) Automated driving of heavy trucks on truck-only lanes, significantly increasing the throughput capacity per lane while reducing the aerodynamic drag and fuel consumption of the trucks.

Mobility-Enhancing Services

The first of the three mobility-enhancing services is the use of speed advisories to improve highway traffic flow. Until now, the available method for regulating highway traffic flow has been ramp metering, which controls traffic volume or average density, but not speed. The VII communication capabilities will make it possible to sample real-time vehicle speed data with unprecedented scope and accuracy and to communicate the recommended speed to each equipped vehicle, which was not previously possible, without the need for expensive gantries and variable message signs. This, in combination with cruise control systems (including adaptive cruise control), gives the highway operator an unprecedented opportunity to directly control the speed as well as volume of highway traffic, so that the effects of traffic disturbances can be minimized and flow can be stabilized to maximize the level of service to highway users.

The second mobility-enhancing service is cooperative traffic-adaptive cruise control, extending beyond the traffic smoothing potential of the speed advisories to enabling significant increases in lane capacity. Current research by the project team has already shown the potential for operating adaptive cruise control (ACC) at smaller time gaps than the current generation of autonomous (sensor-based) ACC by using the vehicle-vehicle communication capabilities of VII to coordinate vehicle responses. The new element proposed here is the addition of information communicated from a wider range of vehicles, so that the cooperative ACC can adjust its set speed and following distance based on downstream and adjacent-lane traffic conditions outside the range of the ACC sensor system. This type of information can only be provided by a VII-like communication capability. It offers the opportunity to achieve lane capacity close to twice as high as today’s capacity (if all vehicles were to use CACC at the minimum time gap), while also smoothing traffic disturbances and making the ACC performance appear more natural and sensible to the driver, increasing driver acceptance.

The third mobility-enhancing service is operation of heavy trucks in automated close-formation platoons, which enables a possible doubling of capacity per lane while reducing aerodynamic drag significantly. Prior research by the project team has shown the technical feasibility of two-truck platoon driving at highway speeds, as close as 3 m apart, and producing fuel consumption savings in the range of 10% to 15%. The new element added here is the extension to a three-truck platoon, which is significantly more challenging technically, and the addition of the vehicle maneuvers that would be necessary for an operational system (trucks joining and leaving the platoon and changing lanes and merging automatically). This research will also show for the first time how the close vehicle-vehicle coordination needed for platoon driving can be achieved using the DSRC communication system under development for VII. If this is successful, it could double the capacity of a truck-only lane, making it possible for a new dedicated truck-way to serve the expected traffic volumes in the highest density corridors in the U.S. with a single lane (plus shoulders) in each direction, thereby substantially reducing the cost and environmental impact of the truck-way.

Technical Background

Freeway traffic speed advisories

Ramp metering is a well-established strategy for controlling the average density of traffic in a highway section, but there is no currently available strategy for controlling traffic speed. In this project, we combine dynamic ramp metering with speed advisories to provide coupled control of both density and speed (based on enhancements of existing models) and coordinated along a freeway corridor.

Variable Speed Limits (VSL) have been tested in Europe to smooth or homogenize the traffic flow along a stretch of highway. A speed limit was enforced when volume approached capacity, and kept constant along a section of the freeway. Several empirical studies have been conducted in the U.S. since the 1960's for different purposes (to improve traffic safety or work-zone safety, or traffic flow) [1]. Recent research in [2] used an empirical approach to investigate the effectiveness of providing feedback to the driver with advisory Variable Message Signs (VMS) in reducing congestion at a recurrent bottleneck. The suggested speed was based on the traffic situation upstream and downstream of the bottleneck. Data analysis showed that driver response to the speed limit and messages on the VMS was reasonable, speed was regulated to some extent, and the improvement in safety was more significant than in traffic, up to 20%~30%. Other work showed that speed control was effective to some extent in reducing speed and speed variations, as well as the number of shockwaves. Moreover, it was particularly effective on the portions of freeway where vehicles maintained small driving headways.

The technical approach in this project is based on our experience and understanding of freeway corridor traffic characteristics through the development of the Performance Measurement System (PeMS) [3] in California, and in traffic modeling, analysis, simulation and optimal ramp metering algorithm development [4,5]. The following two on-going projects provide much of the technical foundation for the new research:

(a) TOPL (Tools for Operations Planning): The TOPL project is developing tools to (i) specify the actions for planned operational improvements; (ii) quickly estimate the benefits that such actions can realize; and (iii) prepare detection plans to support implementation of actions, accurately measure the ex-post benefits of those actions, and compare them with their ex-ante estimates. It will have facilities to model event scenarios such as lane closures. Application of TOPL2 can be easily extended to real-time traffic control since PeMS data can be obtained in real time at 30 s update intervals.

(b) Coordinated Ramp Metering: A near-global coordinated freeway corridor on-ramp metering optimization strategy and Linear Programming numerical algorithm are already available, with on-ramp queue and off-ramp flow constraints taken into consideration [6]. The current project is designing and evaluating freeway ramp metering control algorithms for a test area in Los Angeles and developing and validating freeway corridor traffic models and observers.

Based on the understanding and tools developed in these projects, the new project will dynamically detect bottlenecks and determine the real-time effective capacity of each highway section. Mathematical optimization will be used to select 'Preferred Reference Speed Limit' (PRS), 'Preferred Reference Density' (PRD), and a section-wise ramp metering strategy to maximize effective throughput and minimize the severity of disturbances. Specifically, the project will (a) develop algorithms to determine corridor-wise PRS and PRD based on the macroscopic models from TOPL2 with uncertainties accounted for and compatibility with microscopic models taken into consideration; (b) use PRS as the reference speed feedback to the driver (and to the CACC described below) to improve traffic flow; and (c) use PRD as the reference density for coordinated corridor ramp metering.

Traffic-Responsive Cooperative Adaptive Cruise Control (CACC)

Conventional autonomous adaptive cruise control (ACC) offers an almost unlimited choice of cruising speed, but is limited in choice of gaps that it can provide and the minimum gaps (based on the possibility for the system to safely and comfortably control the gap) that it can offer are often longer than the gaps that drivers wish to maintain in dense traffic. A solution to this limitation of ACC is to enhance the system with wireless vehicle to vehicle (V2V) communication to make the system cooperative (CACC). CACC systems can augment the forward ranging sensor data of current ACC with additional information communicated over the wireless data link from the preceding vehicle (vehicle location, speed, acceleration, braking capability), which makes it possible to overcome the main performance limitations of ACC. CACC-equipped vehicles can be designed to follow the preceding vehicle with significantly higher accuracy and faster response to changes. This makes it possible for the CACC to be used comfortably by drivers at smaller time gaps than ACC, improving highway capacity, and the CACC should be better able to dampen shock waves in the traffic stream based on results from our traffic simulation studies [7].

Although V2V communication allows the use of CACC in denser traffic and can help avoid traffic flow breakdowns in dense traffic, it does not account for downstream congestion in the making. However, a traffic information system using VII to collect probe vehicle data can assess traffic conditions over a wider range than a driver or a CACC, and can therefore recommend a preferred speed and gap size for the near future. The system thus combines the driver's preferences and traffic information inputs for controlling the vehicle speed and gap with respect to the lead vehicle, making the CACC traffic responsive. The innovative aspect of this approach is based on the integration of traffic information in the control logic of an ACC and the use of V2V communication to enable the CACC to operate effectively at shorter gaps than conventional ACC. Both effects should lead to a more favorable impact of CACC on overall traffic flow smoothness and capacity, encouraging the dissipation of bottlenecks, and improved driver acceptance based on the ability to reduce the gap size setting in dense traffic, as drivers do [8], to discourage cut-ins.

Prior PATH research has investigated the impacts of ACC and CACC on traffic flow capacity and smoothness, based on use of a traffic simulation that includes a model of driver car-following behavior developed by the project team [9]. This study has shown that conventional ACC is unlikely to have much effect on traffic, but CACC could lead to significant lane capacity increases if drivers would be comfortable using it at time gaps as short as 0.5 seconds. If the CACC drivers were encouraged to concentrate in one lane of a multi-lane highway, the capacity increases could be substantial, even at modest total market penetration of CACC vehicles.

Truck Platooning

Closely-coupled longitudinal control of heavy trucks offers two significant benefits to trucking operations:

(1) It significantly reduces aerodynamic drag, making it possible for trucks cruising at highway speeds to save 10% to 20% of their fuel consumption and carbon emissions [10].

(2) It can significantly increase the capacity of a truck-only lane, such that a single lane of tractor-trailer trucks operating in 3-truck platoons can handle twice the number of trucks as it would if they were driven individually and manually controlled [11].

PATH has demonstrated the drag savings in scale-model wind-tunnel tests of four trucks and full-scale test track tests of two trucks [10,12]. In the current environment of high fuel prices and growing concerns about global climate change, these savings are significant and valuable. The capacity improvements have been estimated based on kinematic simulations incorporating specific assumptions about safe following distances. These capacity improvements can bring important cost savings to dedicated truck lane facilities, making it possible to accommodate high volumes of truck traffic with fewer lanes, resulting in lower construction and right of way costs [13].

In order to achieve these benefits, it is necessary to have a longitudinal control system on the trucks that can maintain close separation with high accuracy and smooth ride quality. This vehicle following system needs to be cooperative, including active communication of data between the trucks with high reliability and sufficiently frequent updates.

One of the main problems for vehicle following control is maintaining string stability [14] under the disturbances caused by measurement errors and time delays. This requires rapid control system updates and limited uncertainties in measurement data. The main uncertainties are time delays, model mismatches (differences between the actual vehicle dynamics and the model used for control design), control saturation (engine torque significantly decreases as vehicle speed increases), and unexpected environmental disturbances (wind, unevenness of the road, …). The delay sources include: sensor measurement delay, actuation delay, and inter-vehicle communication delay. The former two are determined by vehicle design characteristics and physical limits of sensors and actuators.

The inter-vehicle communication delay depends on the wireless technology that is used. The vehicle follower control systems previously implemented by PATH have relied on update intervals of 20 or 40 ms, corresponding to 50 Hz or 25 Hz update rates. Since DSRC is being designed for an update rate of 10 Hz, this project will determine whether acceptable vehicle following performance can be achieved with that slower update.

A deployable truck platooning system needs to include cooperative maneuvering capabilities as well as the ability to maintain close following within the platoon. This means that the vehicle-vehicle communication link also needs to support cooperative lane changing and merging of trucks into the traffic stream, trucks attaching themselves to the end of a passing platoon and trucks separating themselves from a platoon to exit the roadway. All of these maneuvers will be designed and tested in the project.

Logical Flow for Traffic Management

The logical flow of information for the two traffic-management related functions (speed advisories and CACC) is shown schematically in Figure 1. These functions will be implemented in prototype form for the research project, which is somewhat different from their expected implementation when a mature VII system is deployed. The shaded blocks on the right side of Figure 1 represent functions associated with the evaluation of effectiveness in the research project, but would not be part of an eventual deployed system. The stages in the logical flow of system operation are:

1. Collection of data about real-time traffic conditions. Under current conditions, and for purposes of the experiments to be conducted in this project, this will be done using the existing inductive loops installed in the Berkeley Highway Laboratory (BHL) section of I-80 and the BHL video cameras adjacent to I-80. The inductive loop data are archived in the Performance Measurement System (PeMS) database, and the video data are recorded separately. The video data in particular will be used to trace the trajectories of the equipped test vehicles, which will have distinctive marking patterns on their roofs, to show how the adjacent vehicles interact with them when they are traveling at a recommended speed that is slower than the prevailing speeds of their neighbors. In the future real-world deployment, the data collection could be done using probe vehicles equipped with VII wireless capabilities.

2. Data cleansing. The raw data from all the existing sources must be fused, filtered and smoothed. Outlying data points need to be removed and missing data points may need to be imputed based on the available data, so that a comprehensive body of data is available for estimating traffic conditions. Data from multiple sources will be fused for more accurate and reliable traffic parameter estimation. For the experimental implementation during the project research, the data sources will be the inductive loops and video cameras of the BHL on I-80, while for eventual deployment they are expected to be the existing inductive loops and the VII vehicles acting as traffic probes, potentially augmented in some locations by roadside radar or video systems.

3. Traffic parameter estimation. Based on the smoothed and filtered data, the aggregate characteristics of the traffic are estimated as functions of location and time: traffic speed, density and flow rate. The VII probe vehicles can provide speed information essentially continuously in time and space, representing an improvement over conventional infrastructure-based point detectors.

4. Real-time congestion onset detection. For the experimental implementation, this will be done using the BHL loop detectors and video systems. With VII probe vehicles eventually providing traffic data continuously in space and time, both the time and location of congestion onset will be readily detectable everywhere.

5. Predicting uncertainties in driver responses. The driving population is highly diverse and different drivers respond differently to speed limits, especially if those limits are significantly lower than the speeds at which they are accustomed to drive. One of the experiments with naïve drivers in this project will compare the displayed advisory speeds with the speeds the drivers actually choose to drive, to develop an initial calibration. Future research may include use of roadside variable message signs to display speed limits to all drivers on an instrumented highway section, where their actual responses (driving speeds) can be measured to provide more extensive calibration. Based on the observed distribution of driver compliance with advisory speeds, the appropriate advisory speed can be chosen to produce the desired range of actual traffic speeds (in effect, providing the correction factor for driver non-compliance)

6. Macroscopic traffic simulation. An extended Cell Transmission Model (CTM) of traffic conditions is used to predict the future evolution of traffic conditions in space and time, based on the measured data, estimated traffic parameters, and identifications of congestion onset. Currently, the CTM implemented in the TOPL simulations (both Aurora and CTMSim [16]) is for ramp metering only, which means that only first order density dynamics are represented. This will be extended to second order, including speed dynamics, in this project. Since PeMS data can be updated in real time every 30 s and the BHL data can be accessed in real time, those data can be fed into the extended real-time TOPL model for simulation and traffic control purposes. The time horizon used for traffic prediction depends on the algorithm used for traffic control design.

7. Real-time capacity estimation and uncertainty prediction. Most ramp meter control strategies are based on the capacity of the highway section: the flow rate after traffic enters

from the on-ramp should be slightly lower than the capacity for sustainable flow. The physical capacity of a highway section is mainly determined by factors such as road geometry, number of lanes available, weather and illumination. Road geometry is a constant factor and weather and illumination generally change slowly and can be estimated/predicted accurately. Loss of lane availability due to incidents and increases in traffic volume need to be detected automatically, generally through indirect measurements of vehicle speed or density changes. The nominal capacity of recurrent bottlenecks, including their dependence on time of day, can be determined based on analysis of archived historical traffic data. Non-recurrent bottlenecks are more challenging, requiring continuous online estimation of traffic conditions as a function of location and time, which can be summarized in forms such as the Fundamental Diagram (FD). During the research project, this will be based on the measurements by the loop detectors, which are of course only available at specific locations. In the longer-term VII probe vehicle deployment, vehicle speed data will be available continuously across space and time, enabling faster and finer-resolution capacity estimates.

8. Selection of Preferred Reference Speed (PRS) and Density (PRD). The CTM simulations are repeated for a variety of assumed traffic speed and density conditions, so that the resulting traffic conditions can be assessed. Based on comparisons of these results, the preferred combination of reference speed and density for the section of highway is selected. The selection criteria will be determined in the research, based on standard traffic performance measures such as total travel time, mean speed, and the variability in speed and vehicle spacing across space and time.

9. Selection of ramp metering rate. Based on the selected PRD for the highway section, the preferred ramp metering rates are determined for the ramp meters serving this section.

10. Application of preferred reference speed. The selected PRS is provided as the set speed to the CACC vehicles and as advisory speed to the other vehicles on the highway section.

Because the CACC vehicles have automatic speed control systems, the set speed quickly becomes the actual speed of these vehicles. While they are driving at the set speed, the drivers of the surrounding vehicles will have no knowledge of this set speed and will be driving at their respective preferred speeds and following distances. The interactions between the equipped vehicles and the surrounding vehicles will be observed by the BHL video tracking system, which will make it possible to analyze these interactions afterwards to see how effectively the equipped vehicles could influence the speeds of their neighbors, and whether their slower travel led to excessive lane changing by vehicles behind them whose drivers wanted to go faster.

The recommended speed advisory is displayed to the drivers of the test vehicles in experiments when they are not operating under ACC speed control. In this case, the willingness of the drivers to follow the advisory speed will be observed, particularly as a function of the amount by which it differs from the prevailing speed of traffic surrounding them. When they do modify their speed in response to the advisories, their interactions with the surrounding vehicles will also be observed by the BHL video tracking system, as in the CACC case.

In the future VII-based implementation, much larger numbers of vehicles would be able to receive the CACC set speeds or advisory speeds, but it is not possible to test the effects that this would have using only the two available test vehicles. Those effects will be estimated using traffic simulations, where the interactions between equipped and unequipped vehicles will be represented based on the BHL observations of these interactions with the test vehicles.

Users and Stakeholders and their Roles and Responsibilities

The VII program as a whole has a wide range of stakeholders who need to be engaged in the system definition, development, deployment and operation. In addition to that stakeholder foundation, the individual transportation services to be implemented based on VII involve further stakeholder interactions. These are expected to be somewhat different for the traffic speed advisories, traffic-responsive CACC and truck platooning services considered in this project.

Traffic speed advisories

Although the typical VII stakeholder categories of transportation operating agencies and automotive companies are certainly involved here, as they are with all VII-based services, the drivers of the vehicles will have a particularly strong but uncertain influence on the effectiveness of this service. In order for this service to have an effect on traffic conditions, drivers will have to choose to rely on it. At this time, there is no applicable experience in the U.S. to indicate the likelihood of success. European experience has indicated that strong police enforcement of variable speed limits has promoted widespread compliance (within a 10 km/h cushion above the displayed limit), but implementing such enforcement here will require commitments and prioritization by elected officials as well as the police.

Traffic-responsive CACC

The issues for drivers are similar to those identified above for traffic speed advisories, but with the additional need for the drivers to be motivated to transfer part of their speed and spacing control responsibilities to an automated system. This motivation will have to be strong enough to support the significant additional cost associated with equipping a vehicle with ACC (and to convince the automotive suppliers and OEMs to include that feature in a sufficiently wide range of vehicle models that it can become affordable to a substantial proportion of the public). The automotive industry organizations will also have to agree on performance standards for cooperation among ACC systems on different makes of vehicles, beyond the basic VII data content and communication standards.

Truck platooning

Truck platooning involves a significantly different combination of stakeholders, in addition to the core VII stakeholders:

- truck fleet operators to be convinced that this will make economic sense for them and that they should therefore equip their trucks;
- truck manufacturers and subsystem suppliers to be convinced that their customers want to have this capability and are willing to pay a price that will be profitable;
- truck drivers to be convinced that this will improve their quality of life rather than being a burden on them or a threat to job security;
- public infrastructure authorities to be convinced of the advantages of providing separate truck-only lanes where this capability can be implemented;
- insurance companies to be convinced that this does not adversely affect safety, so that it does not lead to premium increases.

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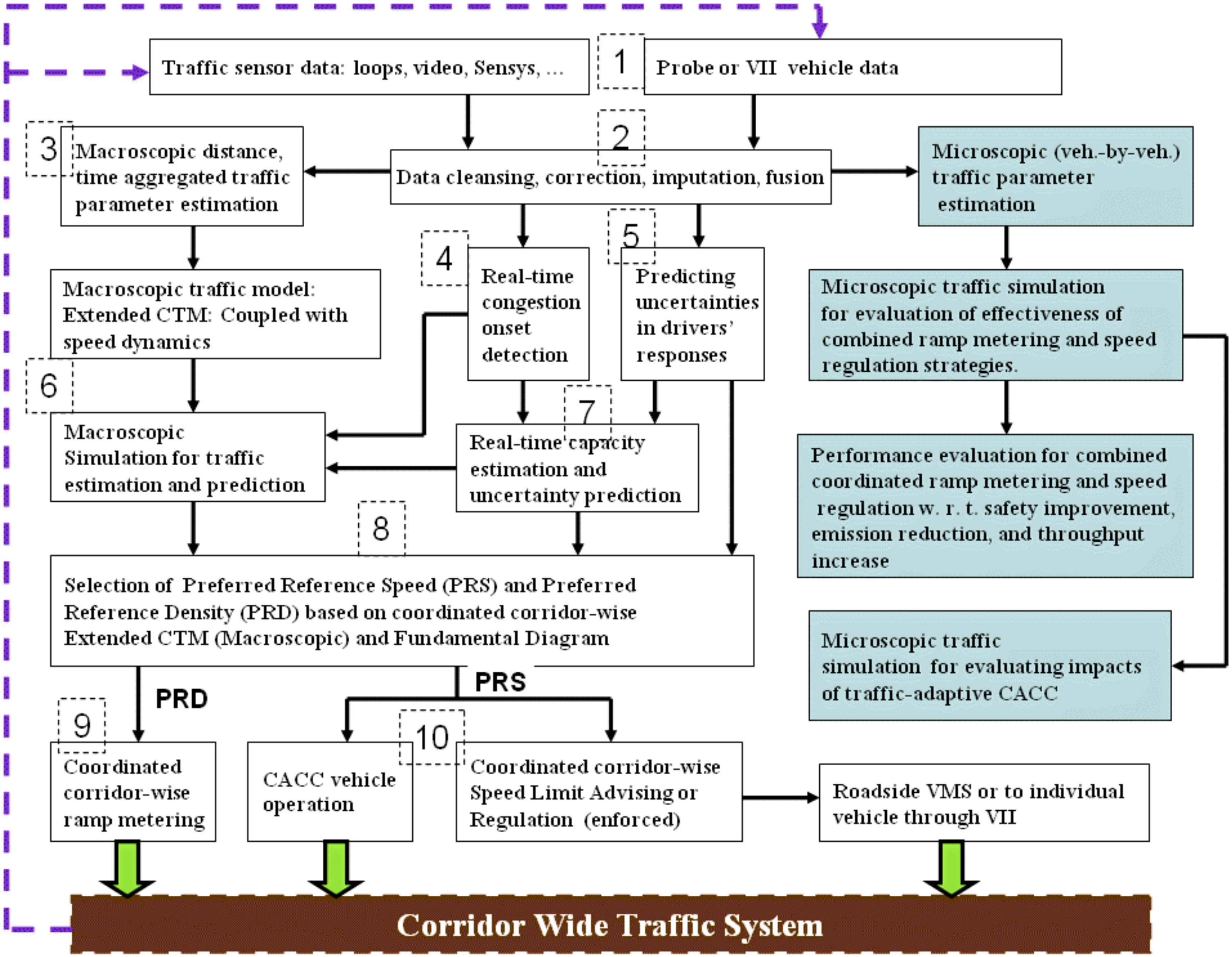
1
Traffic sensor data: loops, video, Sensys, …
Probe or VII vehicle data
2
Data cleansing, correction, imputation, fusion
3
Macroscopic distance, time aggregated traffic parameter estimation
Microscopic (veh.-by-veh.) traffic parameter estimation
Macroscopic traffic model: Extended CTM: Coupled with speed dynamics
4
Real-time congestion onset detection
5
Predicting uncertainties in drivers' responses
Microscopic traffic simulation for evaluation of effectiveness of combined ramp metering and speed regulation strategies.
6
Macroscopic Simulation for traffic estimation and prediction
7
Real-time capacity estimation and uncertainty prediction
Performance evaluation for combined coordinated ramp metering and speed regulation w. r. t. safety improvement, emission reduction, and throughput increase
8
Selection of Preferred Reference Speed (PRS) and Preferred Reference Density (PRD) based on coordinated corridor-wise Extended CTM (Macroscopic) and Fundamental Diagram
Microscopic traffic simulation for evaluating impacts of traffic-adaptive CACC
PRD
PRS
9
Coordinated corridor-wise ramp metering
CACC vehicle operation
10
Coordinated corridor-wise Speed Limit Advising or Regulation (enforced)
Roadside VMS or to individual vehicle through VII
Corridor Wide Traffic System