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PREPARING TO USE VEHICLE INFRASTRUCTURE INTEGRATION IN TRANSPORTATION OPERATIONS: PHASE I

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Abstract:

The close integration of vehicles and the infrastructure in the surface transportation system has been envisioned for years, but recent advances in wireless communications has made such integration feasible. Given this feasibility, a coalition of the public and private sectors is currently exploring the national deployment of vehicle infrastructure integration (VII), based on the relatively new Dedicated Short Range Communications (DSRC) standard. The Virginia Department of Transportation (VDOT) is a member of this coalition, known as the National VII Coalition.

Most of the effort at the national level is focused on technology aspects and study of safety benefits. In order to best inform design, deployment and operations decisions, it is also necessary to fully evaluate potential VII-enabled operations applications. This research effort focused on the development of a simulation environment to model VII and associated operations applications. This model was then used to begin to explore implications of VII design decisions on the potential for VII to support traffic operations.

A major contribution of this research was the development of a high resolution VII/traffic simulation environment. This environment uses AIMSUN for traffic simulation, integrated with custom code that emulates VII functionality. Using this model, VII roadside units (RSUs) were "placed" based on guidance from VII architecture and the extent of VII coverage was determined. A prototype traffic monitoring application was developed and evaluated for various penetration rates of VII equipped vehicles on an urban traffic network in the Tysons Corner area.

The results of this study identify the important factors that influence the benefits that VII can provide for traffic monitoring. It was found from this study that based on current guidance in the VII Architecture, roughly 55% of the sections in the network would be within the direct range of an RSU. The accuracy and coverage analysis of the network illustrated that, based on the current VII architecture, around 60% of the network could be "covered" at low penetration rates. The error range for mean speed estimation was in range of 2.5 to 4 mph, even at very low VII penetration rates.

Based on these findings, it is clear that potential benefits of VII are significant. However, given the sensitivity of the benefits to RSU deployment (which will require substantial investments in terms of installation and maintenance), the costs of VII will also be significant. As more information about the final national VII design becomes available, the simulation environment developed in this research can be used to conduct detailed benefit/cost analyses. Finally, the findings of this research support the need for VDOT to remain actively involved in VII development efforts and to expand VII research and evaluation efforts in the areas of operations applications.

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ABSTRACT

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INTRODUCTION

The close integration of vehicles and the infrastructure in the surface transportation system has been envisioned for years, but recent advances in wireless communications has made such integration feasible. Given this feasibility, a coalition of the public and private sectors are currently exploring the national deployment of vehicle infrastructure integration (VII), based on the relatively new Dedicated Short Range Communications (DSRC) standard. The Virginia Department of Transportation (VDOT) is a member of this coalition, known as the National VII Coalition.

While the possibilities offered by VII are abundant, it is important to explore fully the potential benefits that VII deployment can offer in order to guide decisions. Several efforts are being undertaken for the evaluation of VII benefits, but the majority of these activities are focused on safety applications. However, given the unprecedented capabilities that VII offers for data collection and transmission, it is expected that VII will enable significant improvements in system operations. For example, it is expected that VII will support improved traffic signal control and freeway management. In addition, a key supporting capability for operations, as well as traveler information services, is traffic monitoring. VII will offer the opportunity to collect large quantities of “probe” vehicle data – potentially providing accurate real-time link travel times and speeds. However, it is important to remember that this is potential, the actual ability of VII to deliver quality traffic monitoring data will be dependent on numerous factors, including the actual nature of VII infrastructure deployment, message transmission supported by VII, level of VII equipment “penetration” in vehicles, and the algorithms deployed that govern vehicle sampling and data consolidation. To put it simply, this application, as with others, should be explored fully before deployment decisions and investments are made.

Because of this need, VDOT initiated a VII research program to help guide its participation in the National VII Consortium. The focus of the program is to develop a research infrastructure to evaluate operations applications of VII, and then to test high-priority applications. This report presents the findings of Phase I of this research program; Phase I focused on development of a VII simulation environment and preliminary testing of operations applications. Subsequent phases will focus in more depth on operations applications.

PURPOSE AND SCOPE

The purpose of Phase I of the VDOT VII research program was to create a VII simulation environment that could be used to evaluate benefits of operations applications, and to conduct a preliminary evaluation of a VII-based traffic probe monitoring application. The scope of this effort was limited to simulation; the research did not include field demonstrations or evaluations.

METHODS

This section describes the four tasks completed in order to meet the objectives of this research effort.

1. *Literature Review:* To serve as a background for this effort, the research team conducted a review of existing VII documentation. Most of the documentation considered was produced by the National VII Consortium.

2. *Development of VII Simulation Environment:* The purpose of the VII simulation environment is to emulate the functional capabilities of the VII system. The focus in developing the simulation environment was to support interactions between applications that utilize the VII infrastructure in addition to emulating the communications functionality of VII. In order to develop the VII simulation environment, an architecture was first developed. The development of the simulation architecture was based on the study of existing simulations used for modeling inter-vehicle communications (Mangharam et al., 2005; Wu et al., 2005). The final architecture was developed based on the following considerations.

    - The aim of this simulation environment was to allow applications to interact with the VII system and with one another. Thus, the environment emulated the VII communications infrastructure at a functional level, while detailed technical simulation of communications was unnecessary.
    - In order to maintain the maximum flexibility, all VII functionality took place "outside" of the traffic simulator. Thus, the traffic simulator used in the architecture could be any commercial off-the shelf simulation tool.
    - In order to facilitate data storage and exchange between the simulator and various applications, a provision was made for the inclusion of a generic "clearinghouse"

database. This inclusion allowed dynamic interaction between various applications and the traffic simulator.

- A layered architecture was preferred. The design of this architecture was such that a single module, the VII Interface Module, handled communications between all other components.

3. *Evaluation of Road-side Unit (RSU) Coverage:* In this task, the research team used the VII simulation environment to evaluate the spatial coverage provided by a likely RSU coverage configuration for a traffic monitoring application. A fundamental consideration of the deployment of VII in a region lies in the placement of RSUs. The VII Architecture specifies RSU spacing of roughly 10 miles for rural freeways. No similar value is provided for urban freeways, thus, for this study, a spacing of two miles was assumed. Also, since the RSU spacing is closer for arterials and especially signalized intersections, the RSU spacing for these was assumed to be 2/3 of a mile. Furthermore, given that RSUs are envisioned to serve a large number of intersection safety applications, it was assumed that RSUs, by default, would be located at major arterial intersections.

   Based on these criteria, RSUs were configured by the research team with respect to a traffic network being investigated. Once the RSU locations were determined, the "direct" traffic monitoring application coverage was determined based on the sections (links) and intersections that were within direct communication range of the RSUs. A section was considered covered by the RSU if both the section end coordinates fell within a radial distance equal to the typical communications range of the RSU as stated in the VII Architecture (300 m). In the case of an intersection, if the mid point of the intersection fell within the radial distance equal to the range of the RSU, then it was considered to be covered by RSU. If a particular section or intersection was covered by RSU, then all VII equipped vehicles in that section or intersection were assumed to transmit data to the corresponding RSU.

4. *Development of Traffic Monitoring Application:* The research team developed a prototype traffic monitoring application for use in the VII simulation environment. The application was designed to generate mean speed, speed variance, mean travel time and travel time variance of all "covered" sections (links) in the network. There were two different types of "covered" sections in the VII simulation implementation. The first set of "covered" sections referred to those that were within the direct range of RSUs (referred to as "directly covered") and identified by the procedure described in the previous section. The second set of "covered" sections was those for which data was available through individual vehicle data storage (referred to as "indirectly covered") and subsequent transmission upon encountering an RSU. Data obtained for both types of sections was provided to the traffic monitoring application.

   The development of the traffic monitoring application involved the following steps:

- The static input data sets which include RSU Coverage, Static Section and Intersection data were obtained from the simulation at the beginning of the simulation and stored in the application database.
- The dynamic input vehicle data was obtained from the simulator every simulation step.
- The application was configured for a specific reporting interval (in this case 10 minutes).
- The filtered data from the Information Filter was stored by the application in a buffer for a period of one reporting interval. This table contained the instantaneous vehicle speed values and also the section entrance and exit times for each vehicle in a section.
- The application also received data from individual vehicle buffers which store data periodically depending on their speed. This data provided the application with data about "indirectly covered" sections. The format of the data received by the application was the same for both directly covered and indirectly covered sections.
- For both sets of data, mean speed calculation was done considering that each vehicle could provide multiple speed samples while in a section. For all vehicles in the section in the reporting interval, mean speed and speed variance values were computed.
- In case of travel time, the travel time during a particular reporting interval was computed by considering the sample of vehicles that exit the section during the interval. For all vehicles that exited through the section in the interval, mean travel time and travel time variance values were computed.
- An output table was created in the application database which contains Timestamp, SectionID, MeanSpeed, SpeedVariance, Speed Sample, Mean Travel Time, Travel Time Variance and Travel Time Sample. In each reporting interval, a record was updated in the database with the computed values
- The buffer was then updated with the data from the next reporting interval.

A number of assumptions were made with respect to the data availability and transfer processes in developing this algorithm:

- Each vehicle in the network can be associated with a section or an intersection. Given the expected accuracy of the VII system, it was considered reasonable to make this assumption.
- The vehicle storage data is assumed to be completely transmitted upon coming in range of an RSU.
- All equipped vehicle data is assumed to be transmitted to the RSU if the equipped vehicles are in the range of the RSU.

RESULTS

Literature Review

At the national level, documents describing a preliminary VII architecture and probe message processes have been developed by the National VII Consortium. These documents highlight the likely approach that the nation will employ for VII deployment and data collection. Careful review of these documents was conducted in order to identify the most important aspects and incorporate them into the simulation environment in Task 2. A brief summary of these documents is presented below.

The principle components of the VII architecture (ITS Joint Program Office, 2005) are RSUs, OBUs, VII-Message Switches and Applications. The architecture document outlines the functioning of each of these components and their requirements. According to the physical architecture, every vehicle that is equipped with an OBU collects information about itself and surrounding vehicles and stores the information (such as location, operating conditions, etc.) as "snapshots" for an interval of time. Whenever such a vehicle passes an RSU, it transfers all the existing snapshot data to the RSU. It can also receive messages from the RSU regarding network conditions, which can be used for in-vehicle applications, or transmitted to other vehicles. Several hundred RSUs are connected to a single VII Message Switch. For a typical VII system, there would be hundreds of such VII message switches. All network applications register with the VII message switch. All data that is received by a VII message switch is passed on to all registered applications. Thus, the entire VII system functions in a manner similar to the Internet by providing suitable connection between the data source and the applications that use the data.

To complement the architecture, the National VII Consortium has also examined, in detail, VII probe data handling (Sumner, 2006). Key issues addressed include:

- Vehicles collect snapshots in three different ways. Periodic snapshots, event snapshots and start/stop snapshots.
  - Periodic snapshots are collected at frequent intervals, with the interval frequency being set in inverse proportion to the speed of the vehicle (i.e., faster vehicle speed equals lower frequency of snapshot collection or longer snapshot intervals)
  - Event snapshots are collected when specific events like skidding occur.
  - As the name implies, start/stop snapshots are stored whenever vehicles start or stop moving.
- Each vehicle is expected to have a limited storage capacity of 30 snapshots.
- The interval for periodic snapshots is specified as 6 seconds for low speeds (<20 mph) and 30 sec for high speeds (>60 mph). The interval for other speeds is linearly interpolated between these two values.
- The default setting for probe data collection can be modified when in the presence of an RSU but the modification is only limited to the specific RSU.

While the current "state" of the VII architecture was used as the basis in developing the VII simulation environment, the research team took into account that the architecture itself is still under development. Thus, flexibility was incorporated in the VII simulation environment which accommodated additional features which could potentially be available under the VII environment. Additional changes necessary for computational purposes were also incorporated into the simulation environment. The following section describes the simulation development in greater detail.

Development of VII Simulation Environment

A high level overview of the VII simulation architecture developed in this research is displayed in Figure 1. The main components in this architecture are the Traffic Simulator, the VII Interface Module, Generic Database and the Applications. Each of these components is described briefly here. A more detailed explanation of the simulation architecture can found in Tanikella et al. (2007).

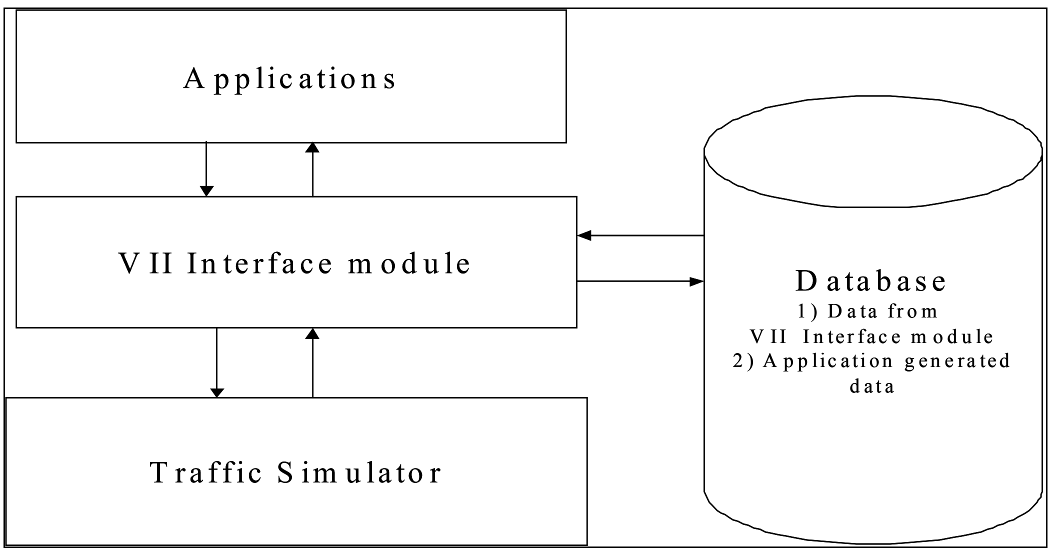

Figure 1: VII Simulation Architecture

Traffic Simulator

The traffic simulator provides an abstraction of the "real" road network, along with the control systems and vehicles using the road network. Since in reality, VII data is obtained from the vehicles traversing the road network, the traffic simulator is considered as a source of all current data for the simulation environment. In order to dynamically interact with the simulator and obtain current data, it is necessary to use the Application Programming Interface (API) provided by the commercial traffic simulator utilized. The crucial task in the development of the VII simulation environment is the coding of API functions to interact with the simulator. In the current implementation, the commercial traffic simulator AIMSUN NG is used as the traffic simulator.

Generic Database

The purpose of the generic database is twofold. The first is to function as a storage area of the "raw" simulation data every simulation second, so as to provide highly detailed "ground truth" data. The second function is to provide a common point for data storage and transfer for applications. The provision of this generic database allows applications to access data provided by other applications. This provision could, for example, be useful in integrating two separate applications such as signal control and route guidance system.

Applications

The applications are external functions supported by VII, such as traffic monitoring, and signal control, that use the information generated by the simulator or the information from other applications, to modify the state of the network through information provision to travelers (thus changing decision processes), or infrastructure control changes.

VII Interface Module

The VII Interface Module is the crux of the VII simulation environment. It acts as an interface between all the other components. In the real world, the VII interface module is the representation of the entire communication network overlay including the RSUs and the VII Message Switches. The VII Interface Module has three main functions, which are described below.

1. The module interfaces between the simulator and database, storing the simulator dynamic data obtained through the traffic simulator API. Thus, the generic database at any instant contains an abstract version of the traffic simulator (or the "real" world).
2. The module interfaces between the traffic simulator and applications by converting the traffic simulator data into a suitable message set format which can then be presented to the applications. The VII Interface Module enables application subscription to required message sets which are filtered from the simulator data based on the location and availability of RSUs. Thus, the VII Interface Module acts as a means of data and message transfer between the simulator and the application fulfilling the functionality of VII in the real world. The VII Interface Module also updates/modifies the simulation data based on message sets created by the applications. This enables applications to control the simulation and modify its state.
3. The VII Interface module acts as an interface between the application and the generic database. This interaction permits data sharing between applications. The VII Interface Module collects data and message sets from the application and stores them in the database. Upon request from another application, the VII Interface module retrieves these message sets and provides them to the requested applications.

VII Simulation Implementation

Based on the architecture described above, the simulation environment was implemented. The VII Interface Module contains the principle components of the FHWA VII architecture such as the Message Switch and RSUs. The Message Switch component contains all the registered applications and their subscriptions. It is responsible for the message delivery to the applications as well as scheduling data delivery when multiple applications exist. A number of RSU components are included, based on the transportation network configuration. An RSU acts as the relay between the Message Switch and the transportation network. In addition to these, other necessary components were identified to be (1) a Network Snapshot component which temporarily stores the simulation data until it is passed to the application, (2) an Information Filter that is used to filter the data obtained from the traffic simulator based on the RSU coverage, (3) a Data Organizer interface with the generic database that enables data storage and retrieval, (4) a Dynamic Controller that handles the application control of the simulation and (5) the Statistics Collectors that aggregate statistics regarding the performance of the VII Interface Module. Figure 2 provides a full visual description of the VII Interface Module, as well as its relationships with other modules.

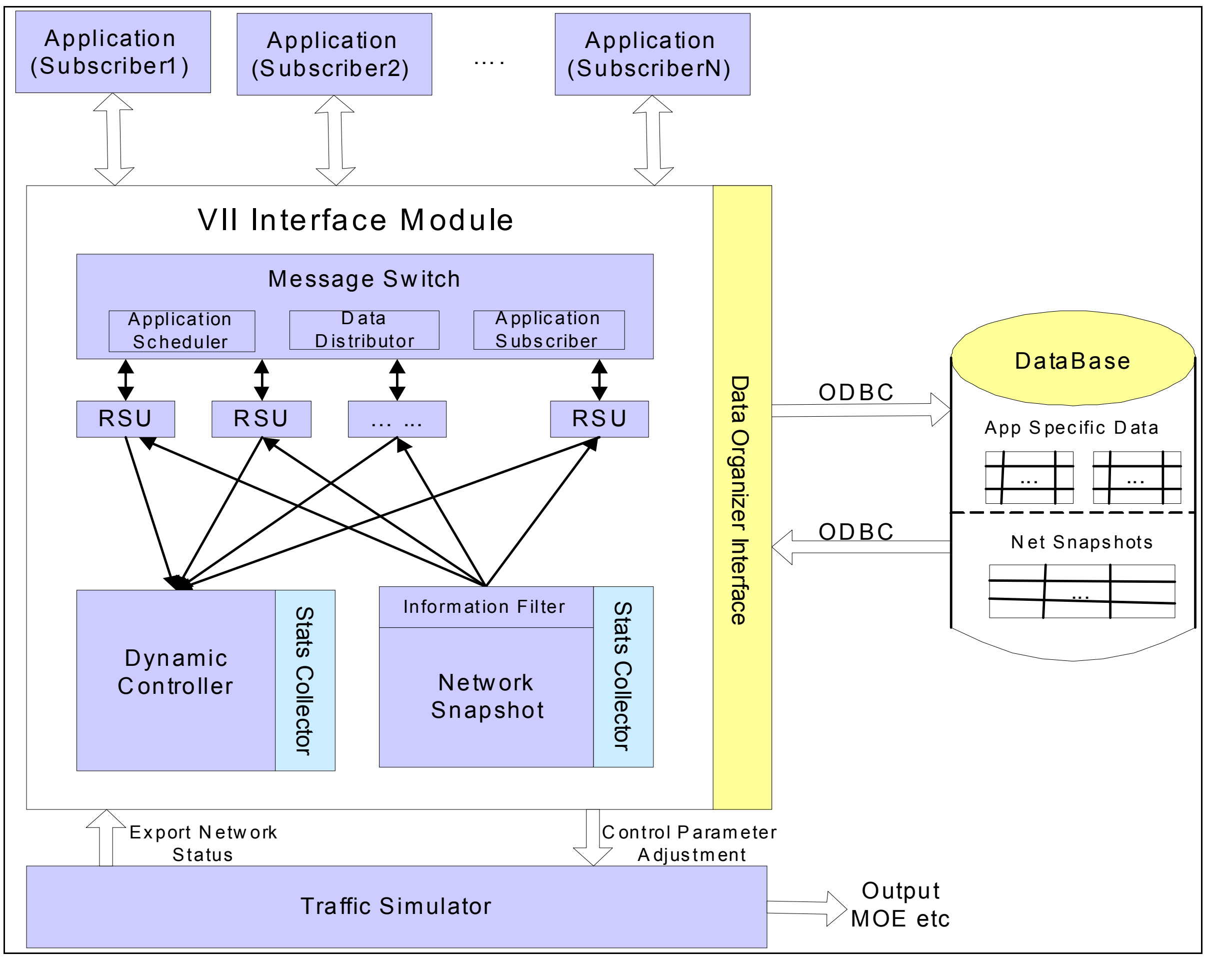

Figure 2: VII Simulation Environment- VII Interface Module

Simulation Process Flow

Using the simulation architecture described above, the simulation process flow is as follows

1. Every simulation step, selected data categorized into message sets are stored in the Network Snapshot. This network data using the Data Organizer Interface is also stored in the Generic Database.

2. The messages are filtered based on the RSU coverage and then sent to the corresponding RSU.

3. The RSUs forward the messages to the Message Switch.

4. The Message Switch selects messages based on application subscribed requirements. The available messages consist of static and dynamic messages.

5. The messages are delivered to the registered applications through the Data Distributor.

6. Once the data is provided to the application, the application, based on its requirements, collects the data in a temporary buffer for a given amount of time or interval. It then processes this data from the temporary buffer to generate the desired output.

7. In case an application needs to send messages back to the simulator, the VII interface module facilitates the transfer.

As can be seen from the above process, in order to provide data to the applications, it is necessary to determine which data would be available based on the location and range (i.e., configuration) of the RSUs. RSU coverage of the road network determines the extent and quantity of data that will be available to the applications. In the next stage of the research, the simulation environment was used to investigate the impact of RSU location on a traffic monitoring application's spatial coverage.

Evaluation of Road-Side Unit Coverage

The methodology for evaluation of RSU coverage, described earlier, was applied to a heavily traveled suburban network, the Tyson's Corner region of Northern Virginia. Figure 3 illustrates the geometry of the network, as well as the RSU configuration created by the research team. Based on this RSU configuration and the rules for determining coverage, it was determined that this VII implementation can provide "direct" traffic monitoring data coverage for 55.7% of all sections and 97.5% of all intersections. The percentage of sections and intersections covered was also determined separately for key routes. Since the rules space RSUs further on freeways, it was found that interstate facilities are the least covered at 26.6%. Rt. 267 has coverage of about 52.3%. The arterial routes, Rt. 7 and Rt. 123, are covered to a fair extent of 70% to 80%. Table 1 provides complete results for traffic monitoring coverage based on the RSU configuration.

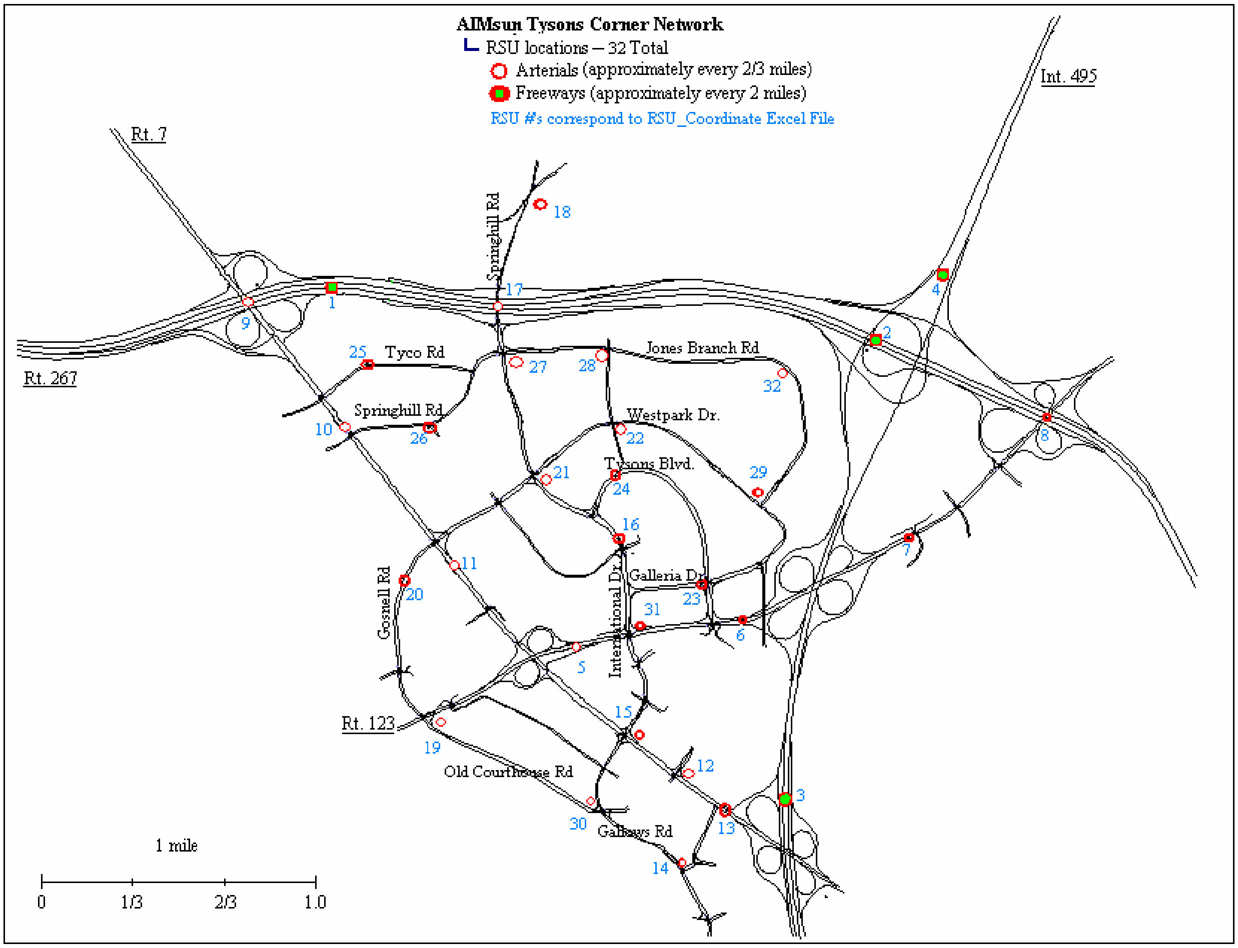

Figure 3: Tysons Corner RSU Configuration

Table 1: Tyson's Corner Traffic Monitoring Coverage

RSU Coverage	Network		I-495		Rt.123		Rt.7		Rt.267	
	Sections	Intersections	Sections	Intersections	Sections	Intersections	Sections	Intersections	Sections	Intersections
Total Number	592	40	64	—	41	9	75	11	71	4
Number Covered	330	39	17	—	32	9	61	10	37	4
% covered	55.74	97.50	26.56	—	78.05	100.00	81.33	90.91	52.11	100.00

Development of Traffic Monitoring Application

Once the traffic monitoring application was developed as described in the methodology, the simulation environment was used to evaluate its ability to generate estimates of roadway link speeds. In addition, the evaluation considered the ability of the application to generate accurate speed estimates. The evaluation was conducted using the Tysons Corner network described above. This network consists of a total of 592 sections and 40 intersections and belongs to the category of a heavily traveled urban network consisting of freeways, major and minor arterials. The input data provided for this network included traffic volumes and turning percentages. In order to maintain consistency, the input volumes were based on data collected in the real world. The total number of vehicles processed through the network for 1 hr of simulation was 42,000 vehicles.

Mean link speeds generated at 100% VII penetration rates provided full population information and thus serve as the benchmark for this evaluation. In order to conduct the evaluation, the simulation was run for a period of 1 hour (with a network pre-loading period of 30 minutes) with varying percentages of VII-equipped vehicles. The output from the traffic monitoring application was retrieved from the database for each different value of the penetration rate. The percentage values considered in the evaluation are 1% to 10% in steps of 1 and 10% to 100% in steps of 10. The lower percentage values (1%-10%) were chosen since in the early stages of VII deployment, the equipped vehicle percentages would be quite low.

The analysis of coverage based on RSU configuration described in the previous section provides information on sections that can feasibly be monitored. However, in reality, the actual data coverage of a network is dependent on the percentage of equipped vehicles as well as the data availability based on vehicle snapshot data storage. Therefore, coverage was independently determined for both the "directly covered" (i.e., within road segments within communication range of an RSU) as well as "indirectly covered" segments (i.e., road segments outside of RSU communication range, but "captured" within the stored snapshots delivered by vehicles). Table 2 shows the proportion of segments for which speed estimates could be generated, based on different percentages of VII-equipped vehicles. It can be seen that for the Tysons Corner Network, considering the combined direct and indirect coverage, even with only 1% vehicles equipped with VII, nearly 60% to 80% of the network is "covered." It can also be seen that the coverage increases rapidly with increases in VII penetration rates, reaching about 90% coverage at 20% VII penetration rates. From the table, it can also be observed that with a default vehicle buffer storage limit of 30 snapshots, indirect coverage or coverage of network through vehicle storage contributes to a considerable portion of overall network coverage increasing from 24% at 1% equipped vehicle percentage to a maximum of 37%%, which is at 20% penetration rate.

Table 2. Speed Estimate Availability as a Function of VII Penetration Rate

VII Penetration Rate	Speed Estimate Availability		
	Direct	**Indirect**	**Total**
1	0.35	0.24	0.59
2	0.43	0.31	0.74
3	0.48	0.33	0.81
4	0.50	0.34	0.84
5	0.51	0.35	0.87
6	0.52	0.35	0.87
7	0.52	0.35	0.87
8	0.52	0.35	0.87
9	0.52	0.35	0.88
10	0.53	0.35	0.88
20	0.54	0.37	0.90
30	0.55	0.37	0.92
40	0.55	0.37	0.92
50	0.55	0.37	0.92
60	0.55	0.37	0.92
70	0.55	0.37	0.92
80	0.55	0.37	0.92
90	0.55	0.37	0.93
100	0.56	0.37	0.93

However, the specific results observed here are dependent on the location of RSUs in the network and will vary depending on the RSU configuration.

Next, considering the sections where traffic variable estimates were feasible, absolute speed estimate error values were computed. This computation was performed separately for direct and indirectly covered sections. Figure 4 illustrates the mean error for mean speed at different VII penetration rates. It can be seen in the figure that, as expected, the error follows a decreasing trend as VII penetration increases. It can also be seen that even at very low levels of VII penetration, speed errors are remarkably low (on the order of 3 to 4 mph). Thus, this illustrates that traffic monitoring will be feasible in the very early stages of VII deployment.

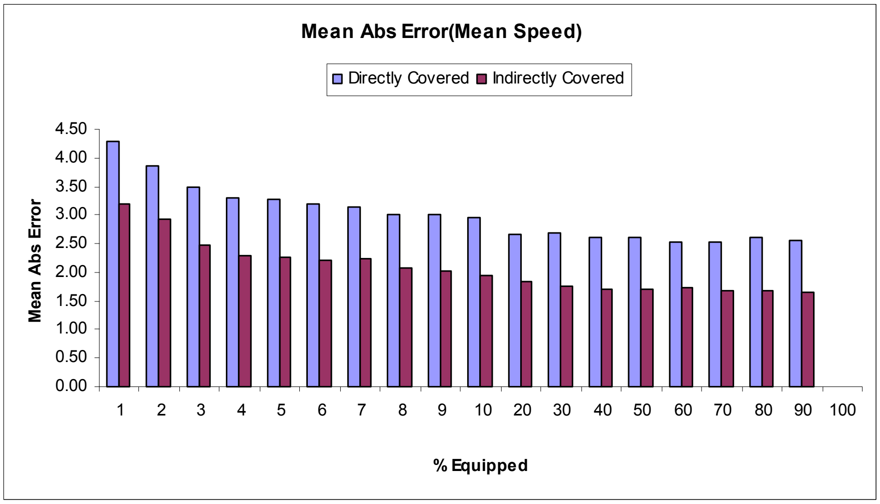

Figure 4: Mean Absolute Speed Error as a Function of VII Penetration Rate

CONCLUSIONS

- *The potential deployment of VII holds considerable promise to improve transportation system operations.* However, in order to realize this promise, it is necessary to thoroughly investigate these applications in a simulation environment in order to inform future VII design, deployment, and operations decisions. The research presented in this report describes the development of a VII simulation environment to evaluate operations applications. A prototype traffic monitoring application is also evaluated within the VII simulation environment.

- *The evaluation of the prototype traffic monitoring application identified important aspects that determine the ability of VII to provide benefits to operations applications.* Two major aspects were considered in this evaluation: 1) The extent of "coverage" RSUs will provide in the network and 2) the accuracy and coverage of network data collected through VII. Based on the guidance of the current VII architecture, nearly 60% of an urban network is likely to be within the direct range of an RSU. This analysis illustrates the significant impact that the specific deployment of VII infrastructure will have on the traffic monitoring application. It also reveals that the deployment of a large number of RSUs can be used to effectively monitor an urban network; even if relatively few vehicles have OBUs installed. Since the installation of RSUs involves significant cost, further study is required to determine if fewer RSUs combined with greater vehicle snapshot storage can lead to adequate coverage of the network

- *Details of the emerging VII design will have significant impacts on the ability of VII to support traffic operations applications.* This illustrates the need for VDOT to be actively involved in VII development efforts and to expand VII research and evaluation efforts in the areas of operations applications.

RECOMMENDATIONS

1. *VDOT's Operations & Security Division should remain actively involved in the National VII Consortium.* Decisions currently being made by the consortium, such as those regarding VII architecture details, will have a significant impact on VDOT's ability to use the data resulting from VII to support operations. As an active member of the coalition, VDOT can be sure that VII development will occur in such a way to support the agency's future needs.

2. *VDOT, through the Virginia Transportation Research Council, should continue to support research to evaluate various configurations of VII parameters to determine those most suitable for deployment.* The preliminary evaluation identified the accuracy of data collection with varying percentages of equipped vehicles. However, the coverage of the network and the accuracy and timeliness of data are dependent on deployment of RSUs and configuration of parameters such as percentage of equipped vehicles and vehicle snapshot data storage limits. This evaluation can help VDOT determine its investment requirements and better participate in the national level decision-making for RSU deployment.

3. *VDOT, through the Virginia Transportation Research Council, should consider extending this research to include sampling issues for a VII-based probe monitoring system.* VII probe-based traffic monitoring will produce large amounts of data. With respect to traffic monitoring, sampling can be used to reduce and collect network-wide data.

COSTS AND BENEFITS ASSESSMENT

Although the VII program is not yet mature enough to allow the quantification of the costs and benefits of deployment, this research clearly demonstrates the potential benefit to VDOT of high-quality traffic data made available through VII. The simulation environment developed in this project will provide the foundation for more sophisticated analyses of both costs and benefits that will vary as the VII architecture is finalized and will allow VDOT to be an informed, active participant in discussions regarding the final architecture.

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