ASSESSING THE IMPACT OF VEHICLE COMMUNICATIONS ON TRAFFIC PERFORMANCE

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ABSTRACT

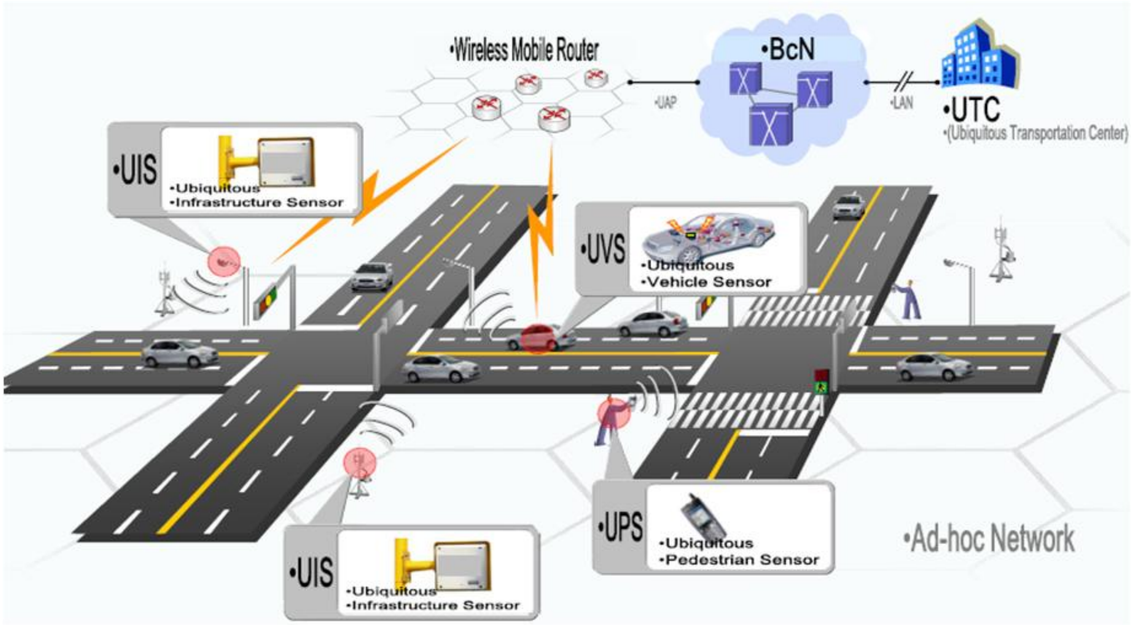
The principal objective of this research was to assess the potential mobility benefits derived from implementing a ubiquitous transportation network, driven by ubiquitous sensors that can communicate information between vehicles and between the fixed infrastructure and vehicles. The selected assessment method was computer simulation. The research team categorized the impacts of u-Transportation at three hierarchical levels: operational, tactical, and strategic. It then defined appropriate tools and performance measures of the impacts for each level. DYNASMART-P (DS-P) was selected as the appropriate meso-scopic simulation tool for the strategic level assessment and AIMSUN was proposed as the microscopic simulation tool for the operational and tactical levels. The work presented herein focuses on the findings from the meso-scopic simulator.

Using DS-P, two pilot test studies were carried out. From these it was determined that traveller information was instrumental in reducing congestion caused by road incidents or flooding events. It was also shown that having access to pre-trip information might not always be beneficial if it is not updated en-route, especially in large networks where traffic conditions may change between the departure time and the time an impacted area is reached. The study also demonstrated that higher u-Transportation market penetration rates will be needed as the spatial and capacity reduction scope of the event becomes more severe. However, the study also indicated that system-optimal protocols, which emulate V2I information systems, yielded larger travel time differentials between diverted and non-diverted vehicles, and therefore the potential for ignoring recommendations for alternative routes. The team proposes that in the future any system optimization algorithm for u-Transportation systems should be able to consider multi-objectives including overall system efficiency (minimum network travel time) and near equity in travel time between OD pairs.

Keywords: Ubiquitous Transportation, Vehicle communication, Mesoscopic simulation, DYNASMART-P, Incident, Intelligent Transportation Systems (ITS), and Traveller information

INTRODUCTION AND OBJECTIVES

Ubiquitous computing is the latest advanced technology that enables human-computer interaction in everyday objects and activities. In fact, the era of ubiquitous computing has already begun in places like Korea. Wire and wireless network infrastructures have been installed all around Korea and most of cell phone users can access the internet and use various services. However, to make the ubiquitous computing technology thoroughly integrated into everyday objects and activities as its definition implies, more intensive research and development are required and investment of government and industries are necessary. To meet this need, the Korean government has been supporting the development and construction of infrastructure of ubiquitous network to build Ubiquitous Korea (u-Korea) which was proposed as the new national management strategy. u-Korea will make significant changes in transportation systems as well. For example, after the ubiquitous networking is realized, vehicle equipped with ubiquitous vehicle sensors (UVS) will be able to communicate with other vehicles and with the roadside infrastructure within a 1-2 km range using dedicated short-range communications protocols. The information that can be transmitted includes position, speed, vehicle heading, and even traffic condition and optimal paths. The Ubiquitous Transportation Center (UTC) will be able to receive seamless and accurate traffic data, so it could produce and provide reliable traveler information, and operate traffic signal controllers more efficiently. The information from other vehicles will help drivers make safe decisions on lane changing, passing, and turning. Based on the information from UTC, drivers will be able to select better travel routes and avoid severely congested areas (Kang et al., 2005). As can be inferred from this example, ubiquitous computing will address many of the limitations in conventional ITS strategies. Various services for pedestrians, transit users, and drivers and most of strategies for operation and management were proposed at the ITS level, but some of them were not feasible because of lack of information and technical limitations. However, under ubiquitous computing, most of those services will be possible to realize, and of course, new services and strategies will be proposed. A vision of u-T is shown in Figure 1.



Source (Kang, 2006)

Figure 1 A Vision of u-Transportation

METHODOLOGY

Specification of Communications Functional Requirements

The core of u-Transportation technology is real time communication between vehicles, the transportation infrastructure, and pedestrians equipped with Ubiquitous Vehicle Sensors (UVS), Ubiquitous Infrastructure Sensors (UIS), and Ubiquitous Pedestrian Sensors (UPS), respectively. A Ubiquitous Transportation Center (UTC) will collect traffic data and transmit traffic information through UIS's. The following describes the two way communications data considered to be developed and transmitted.

- V2V (Vehicle to Vehicle): Vehicles will transmit and acquire position, speed, type, observed incident and congestion and etc. with other equipped vehicles.

- V2I (Vehicle to Infrastructure): Vehicles will transmit position, speed, type, observed incident and congestion and etc. to the infrastructure. The infrastructure will acquire the data from multiple vehicles and provide traveler information such as incident, work zone, congestion information, alternate routes, and so on to equipped vehicles.

- V2P (Vehicle to Pedestrian): Vehicles will transmit position, speed, and type to pedestrians. Pedestrians can send warning alerts when they wish to cross at designated crosswalk.

- I2P (Infrastructure to Pedestrian): The infrastructure will provide many types of information related to transit services and directions outdoors or indoors. Pedestrians can send a signal when they want to cross or board a specific transit vehicle.

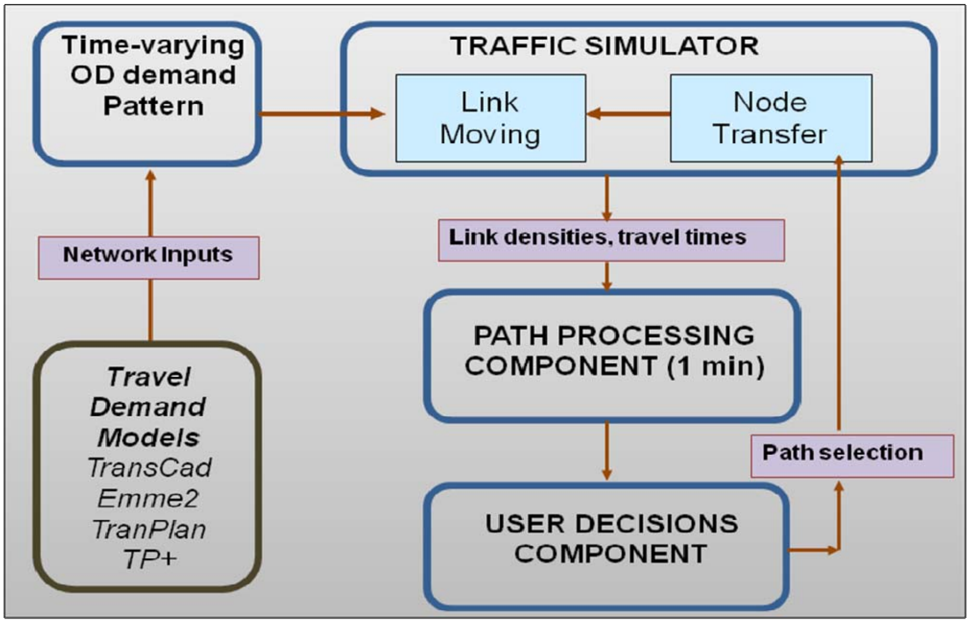
- I2I (Infrastructure to Infrastructure): The information for coordination such as traffic control and management status will be transmitted between the infrastructures.

Anticipated Benefits and Performance Measures

Benefits of u-Transportation can be defined at the strategic (route selection level), tactical (lane selection level) or operational (car following or gap acceptance levels). Strategic benefits include optimal route choice processes; avoidance of bottlenecks and incidents and maximizing the utilization of existing capacity. Measures that reflect those benefits include reduction in delays (min/veh), reduction in overall travel time (min/veh) and an ability to generate high throughputs (veh/hour). At the tactical level processes that can benefit include advance warning of a lane closure to promote better lane selection, and reduce turbulence ahead of closure, and relaying opposing vehicle position which could enable more overtaking without the need for visual confirmation, thus increasing overall 2-lane uninterrupted flow capacity. Performance measures in this case would include measurable decreases in lane changing frequency (in vehicles/km/hr), increases in overtaking rate (in veh/hr/km), increases in freeway and arterial throughput or effective capacity (veh/hour), and decreases in fuel consumption and emissions levels. At the operational level, we may witness an improved merging processes whereby the speed of the vehicle can be changed (via recommend speed on vehicle dashboard) to take maximum advantage of available gaps on the freeway mainline, thus negating the need for ramp metering altogether. The same would apply to a car following process whereby closer spacing between vehicles may be maintained safely without compromising safety, speed or throughput. Performance measures here would be very similar to those described for the tactical level.

Description of Evaluation Tool

A mesoscopic simulation model, DYNASMART-P (hereafter, DS-P) was deemed to be the most appropriate tool for assessing strategic level impacts, since it can model multiple users' behavior over a transportation network on the basis of the level , location where and time when pertinent travel information is received (Mahmassani et al., 1993). DS-P was used in this study for the purpose of developing pilot cases in two test bed networks in Fort Worth, Texas and Knoxville, Tennessee. It gave the team a method to evaluate the network wide benefits of u-Transportation, which is intended to provide real-time information on a large network at the strategic level. It also enabled the quantification of the impacts of varying market penetration levels of the u-Transportation on performance. A high-level diagram of DS-P functionality is shown in Figure 2. It requires a network specification including a variable OD demand matrix, link attributes, a macroscopic speed-flow relationship for each link, and the definition of driver sub-populations based on level and features of the information they receive.



Source (DS-P User Guide, Mahmassani and Sbayti, 2005)

Figure 2 Basic Framework of Dynasmart-P

Modeling Information in the Evaluation Tool

Because modeling mode change, departure time change, and trip cancellation are not currently feasible in commercial versions of DS-P, the team assumed that u-Transportation does not affect changes in mode, departure time, nor destination. The five user classes available in DS-P are described in the paragraphs below. The information user groups via V2V communication and V2I communication were modeled using Class 4 and Class 2, respectively. Other communication types were not considered in this pilot studies.

Class 1 (Historical info)

This class represents drivers who have no access to any information source except for in route variable message signs (VMS). Thus, drivers in this class select routes (normal paths) based on their historical experience, in other words, their travel choice under recurring traffic conditions. They adhere to those paths throughout the entire trip, when not encountering VMS. Normal paths are provided from an initial run which generates vehicles and paths based on OD demand under normal conditions, using user equilibrium assignment rule. Vehicles specified as Class 1 follow paths from the initial run results.

Class 2 (System Optimal, SO)

This class follows the system optimal assignment rule. To minimize the overall network travel time, a small fraction of users (the fraction of Class 2 users) may be assigned to suboptimal routes. This assignment method requires multiple iteration until an optimal solution is reached. This class emulates users who follow the recommended path proposed by the UTC using V2I communications.

Class 3 (User Equilibrium, UE)

This class follows user equilibrium assignment rule. Every driver in this class tries to select the best path to minimize his/her own travel time. Depending on other drivers' path selections, this route might not be the best path. Then, some of those drivers will try other routes in the next iteration. These trials continue until no driver can benefit by switching to another route. We call this route assignment a user equilibrium. This assignment rule is meaningful for modeling long term planning effects. This assignment method requires iterating convergence in OD travel times is achieved.

Class 4 (In vehicle information system, IVIS)

This class models drivers and vehicles that can receive real time travel information in a ubiquitous fashion. Thus, these users update paths at each intersection based on the real time shortest path. This behavior is very similar to drivers who capture travel information via V2V communication.

Class 5 (pre-trip info)

This class represents pre-trip information users. These users select the best path at the start of their travel, then adhere to this path unless they encounter and respond to VMS alerts which may prompt them to divert. There are three types of VMS in DS-p: congestion warning VMS, optional detour VMS, and mandatory detour VMS. The traveler's response rule to VMS is defined based on the selected VMS types.

CASE STUDY DESCRIPTION

The project final report provides details for two case studies, one modeling a typical freeway incident, and the second a river flooding event (Rouphail and Hu, 2008). For the purpose of this paper, only the first case study is discussed. Figure 3 depicts the Fort-worth, Texas network which was used for evaluating the effectiveness of u-Transportation when a single, but severe incident occurs on the network. The network data set was manually coded in the 1990's. The network has since expanded considerably, so this simulation network data may not up-to-date but nevertheless appropriate for the purpose of this work. It is important to note that the impacts of incident and information provision could clearly be isolated in this small network. Basic descriptions of the network include: Number of Nodes: 180; Number of Links: 445; Number of OD demand Zones: 13; Intersection control data: No Control: 87; 4-Way Stop: 31; 2-Way Stop: 1; Signalized:61. The location of the incident and the VMS are shown in Figure 3. The red triangle represents the incident, while the blue rectangle with "VMS" letter represents the VMS positions. The incident is assumed to reduce the impacted link capacity by 75% for 40 minutes. The VMS, which is located further upstream begins to provide the congestion warning before the incident area at 40 minutes. Note that the network topology does not yield reasonable alternative routes for the tested incident location, and therefore the incident is likely to strongly impact overall network performance. Traffic demand varies over time, and exceeds capacity during the incident blockage by a significant margin.

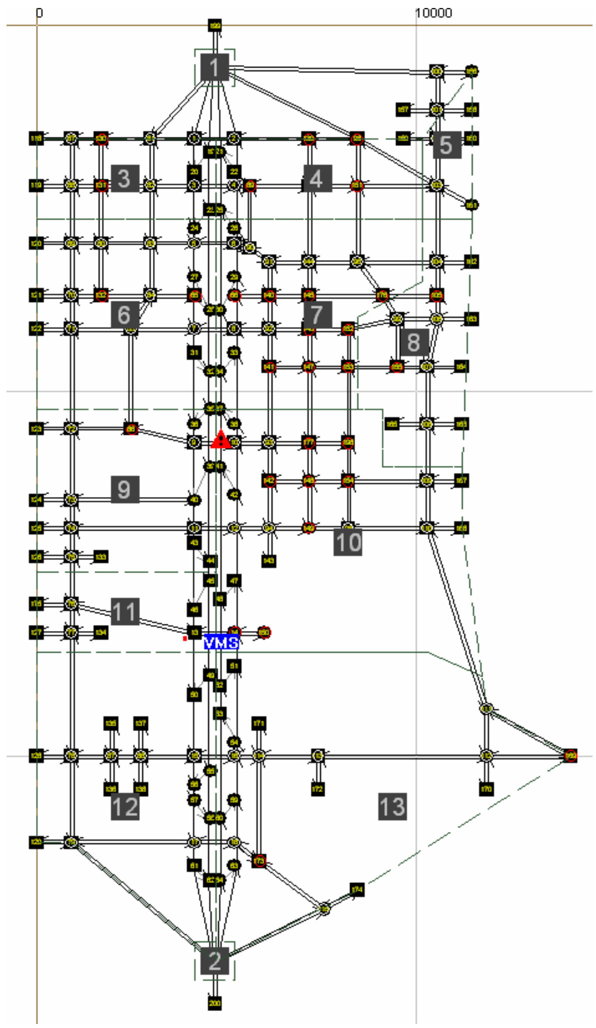


Figure 3 Schematic of Test Network and Key Locations of Incident and VMS

For this case study, multiple scenarios were specified by varying the distribution of user classes defined earlier in this document, in order to test the hypotheses that u-T indeed improves operations in the event of an incident, and the u-T can provided added benefits above and beyond what traditional ITS measures can do.

Table 1 shows 16 scenarios developed for this network. Scenario 1 is the baseline with no incident, while 2 is the baseline with incident but no information (worse case). Scenarios 3-4 have no u-T capabilities but some ITS features. Scenarios 5-16 show progressively increased Market Penetration (MP) of u-T modes whether V2V or I2V. When compared to scenarios 1-4 they will estimate the added value of u-T compared to traditional ITS. In all cases, the meso-scopic model was run until convergence occurred. This does not mean that all the vehicles that desired to enter the network were processed. In fact, the number that did not maybe another important performance measure to consider.

Table 1 Scenario Development of User Information Classes in DS-P

Scenarios		Historical Route (Class 1)	ITS		u-Transportation		
			VMS	Pre-trip Information (Class 5)	V2I (Class 2)	V2V (Class 4)	Total
1	Initial run (no incident)	100%	-	0%	0%	0%	0%
2	Incident-No information	100%	-	0%	0%	0%	0%
3	Incident-VMS	100%	√	0%	0%	0%	0%
4	Incident-ITS	80%	√	20%	0%	0%	0%
5	Incident-u-T 20%/VMS	80%	√	0%	5%	15%	20%
6	Incident-u-T 25%/ITS	60%	√	15%	6.25%	18.75%	25%
7	Incident-u-T 50%/ITS	40%	√	10%	12.5%	37.5%	50%
8	Incident-u-T 75%/ITS	20%	√	5%	18.75%	56.25%	75%
9	Incident-u-T 100%/VMS	0%	√	0%	25%	75%	100%
10	Incident-u-T100%/VMS	0%	√	0%	0%	100%	100%
11	Incident-u-T 20%/VMS	80%	√	0%	15%	5%	20%
12	Incident-u-T 25%/ITS	60%	√	15%	18.75%	6.25%	25%
13	Incident-u-T 50%/ITS	40%	√	10%	37.5%	12.5%	50%
14	Incident-u-T 75%/ITS	20%	√	5%	56.25%	18.75%	75%
15	Incident-u-T 100%/VMS	0%	√	0%	75%	25%	100%
16	Incident-u-T 100%/VMS	0%	√	0%	100%	0%	100%

RESULTS

We present the results on the basis of the most vehicle affected first. One feature of DS-P is its ability to remember the path of each vehicle from a previous run. For example, at the end of Scenario 1 run, we would know which vehicles pass through the position of the (future) incident and keep track of their statistics in the subsequent runs. These are termed “impacted vehicles”. Table 2 shows the impacted vehicle statistics across all runs, whether vehicles “need” to divert and whether they “know” about the incident, based on the scenario information schemes. Drivers are assigned to the different user classes based on random Monte Carlo experiments. It is clear that without diversion (scenario 2), the vehicle travel times increase by more than 5 folds and that the best ITS can do (scenario 4) is increasing the travel time by 4 folds instead, not much of an improvement.

Table 2 Impacted Vehicles’ Statistics for Incident Network

Scenarios	Impacted vehicles statistics				
	Completed vehicle trips (veh)	Diversion rate (%)	Average travel time for (min)		
			Non-diverted vehicles	Diverted vehicles	All impacted vehicles
1	11,537	-	6.17	-	6.17
2	10,693	0%	32.14	-	32.14
3	10,950	6%	27.99	30.46	28.14
4	11,537	16%	23.41	22.03	23.18
5	11,537	21%	20.49	22.48	20.90
6	11,537	30%	14.55	19.89	16.16
7	11,537	30%	14.94	20.12	16.50
8	11,537	28%	13.04	19.80	14.91
9	11,537	27%	13.67	18.59	15.03
10	11,537	21%	16.57	20.95	17.48
11	11,537	21%	19.79	20.42	19.93
12	11,537	30%	15.08	19.48	16.39
13	11,537	32%	10.79	17.78	13.02
14	11,537	32%	10.78	15.52	12.32
15	11,537	33%	10.24	14.93	11.80
16	11,537	35%	9.34	14.77	11.24

On the other hand, a system that has perfect compliance with information gathered and fused by the infrastructure, while not altogether insensitive to the effect of the severe incident, mitigates its impacts significantly, with impacted vehicles travel times increasing by less than double the "normal" time. A couple more observations: scenarios 2 and 3 are unable to discharge the full throughput for the duration of the simulation, and as more V2V and V2I market penetration increases, so does the diversion rate from the initial route followed in Scenario 1, as indicated in the diversion rate column.

A logical question that follows the preceding analysis is: how do those same strategies impact overall network travel? It may very well be that the impacted vehicles have benefited from u-T, but to what extent was that done at the expense of other vehicles. This question is addressed next, as summarized in Table 3 below.

Table 3 Network-wide Travel Statistics by Scenario for Incident Network

Scenario	Network wide statistics					
	Completed vehicle trips (veh)	Incomplete vehicle trips		Average travel time (min)	Average stop time (min)	Average travel distance (km)
		(veh)	(%)			
1	39,647	0	0	5.69	0.69	7.09
2	38,802	845	2.1	16.27	3.79	7.01
3	39,060	587	1.5	15.03	3.61	7.06
4	39,647	0	0	12.92	2.6	7.15
5	39,647	0	0	12.24	2.96	7.23
6	39,647	0	0	10.24	2.19	7.23
7	39,647	0	0	10.32	2.08	7.18
8	39,647	0	0	9.73	1.98	7.20
9	39,647	0	0	9.71	1.96	7.18
10	39,647	0	0	11.18	2.81	7.31
11	39,647	0	0	11.74	3.00	7.17
12	39,647	0	0	10.48	2.57	7.22
13	39,647	0	0	8.73	1.8	7.20
14	39,647	0	0	8.27	1.53	7.12
15	39,647	0	0	8.08	1.54	7.12
16	39,647	0	0	7.88	1.55	7.10

A review of Tables 2 and 3 reveals some interesting insights. First, about 30% of all network vehicles are impacted by the incident (11,537 vs. 39,647), so that incident has network-wide consequences to be sure. Network travel time increases by about 3 folds, and ITS results in an increase of about 2 folds, a decent performance. On the other hand, u-T under optimal control produces an overall network travel time that is only 38.4% above that which occurs under the no-incident condition (Scenario 1).

Interestingly, the diversion rates shown in Table 2 did not result in very long detours for the vehicles traveling on the network. The largest network-average trip distance occurred in scenarios 5 and 6; that distance was about 17% higher than the baseline value. However, diversion from the uninterrupted freeway mode onto the arterial street network with its low operational speeds and large number of traffic signals and other stop and go features also has its price: the impacted vehicles that were diverted had, on average, added from 3 to 7 minutes of travel time on their trip compared to those who did not. So, the efficiency of the system will depend highly on compliance at the optimal level (just the right % of diversions as indicated in Table 2 is required).

Also to be noted the puzzling reduction in average travel distance under scenarios 2 and 3. This is explained by the fact that statistics are gathered only for those vehicles that have completed their trip from origin to destination. In those 2 instances, about 2% of the vehicles were unable to complete the travel, thus biasing the overall statistic downward. It should be noted that vehicles that travel prior to the incident start at simulation time 30 minutes (its effects end 40 minutes later) will report low travel distances and no diversion and therefore effect the reported network statistics.

Finally, we present comparative visual results of the network congestion features under a selected number of scenarios. Each diagram in Figure 4 shows a snapshot of the system at time 80 minutes (after the incident has ended, but with queuing effects at their maximum) and the associated scenario number as labeled in Table 1. Each figure shows colored density contours with green representing free flow conditions (not very visible), and red heavy queued conditions. These graphs are self explanatory and represent another piece of evidence that the u-T contribution at the network level could significantly enhance network performance in the case of severe disrupting incidents.

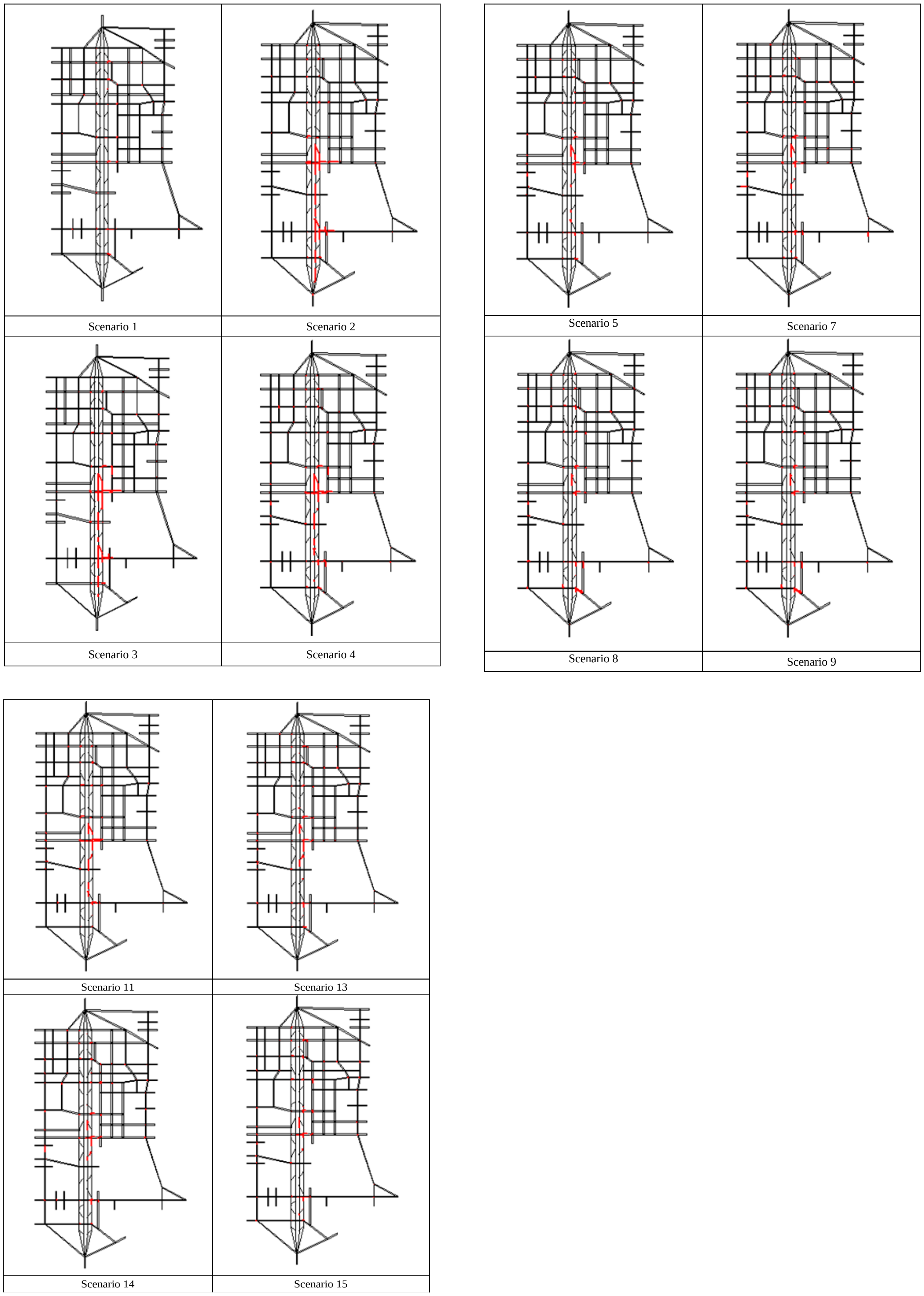


Figure 4.Congestion contours for baseline, incident and selected ITS and u-T scenarios taken 80 minutes from the start of DS-P simulation

CONCLUSIONS

The study objectives regarding the assessment of vehicle to vehicle and vehicle to infrastructure communications protocols, as part of a ubiquitous transportation network (u-T) on traffic network performance have been met. Using a meso-scopic simulator DYNASMART-P as the evaluation tool, various levels of traveler information and response were modelled including pre-trip information, en-route infrastructure based information (e.g. VMS) and in vehicle information from other vehicles and from the infrastructure.

It was demonstrated for a case study that the benefits could be significant and depends on the level of market penetration of the u-T in the vehicle fleet. While communications and information does not and cannot substitute for physical capacity, it is clear that it can mitigate non-recurring congestion effects given that adequate capacity exists elsewhere in the network, and that compliance with diversion information occurs. For the case study network, about 30-35% of impacted vehicles needed to be diverted. Although the diversion distances where not significant, the travel time price was quite high, averaging an additional 5.5 minutes per diverted vehicle (the average trip time for the incident scenarios with some treatment, i.e. Scenarios 3-16 varied from 11-20 minutes). It is unclear whether such levels of courteous behaviour will materialize in the field. In fact, under the V2V scenarios where decisions are made autonomously, the required diversion rate is lower, in the range of 20-25% since this protocol tries to achieve a user-optimum solution.

The presented research has validated the adequacy of the use of meso-simulation for strategic level assessment of u-T systems. Work is underway by the research team to tackle the more complex problem of modelling u-T and u-T responses at the tactical and operational level using higher resolution micro-simulation models, as briefly described in the nest section.

ONGOING AND FUTURE WORK

The next phase of this research program involved the implementation of tactical and operational applications of u-T in a microscopic simulation environment using the AIMSUN model developed by TSS (TSS, 2008). Using application program interface (API), specific algorithms have been added into the model to simulate vehicle-to-vehicle messaging, message interpretation and prioritization and response. Three applications were successfully tested namely dynamic route diversion as a result of V2V communications (similar to the material presented here). In addition, we used V2V to assess whether it can mitigate the shockwave effect of an incident on a link, by promoting smoother speed transitions (also known as Variable Speed Limits or VSL's). Finally, the team also tested several lane evacuation strategies using V2V to minimize delay and travel time by pre-positioning. This work has been presented at the 2010 TRB Conference (Mei et al., 2009), and is expected to be published in an upcoming Transportation Research Board record. Extension of the methods to deal with improved incident alerts in the context of signalized traffic, where the confounding effect of stopping for red lights must be considered, is currently underway.

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