Traffic Operation and Control during Evacuation Conditions: An Integrated Management System with Multi-level Coordination

by Muhammad Zeeshan Khan

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Thesis directed by
Samer Hani Hamdar
Assistant Professor of Civil and Environmental Engineering

Dedication

Dedicated to my mother Shehnaz Akhtar

Acknowledgments

This thesis would not have been possible without the guidance of my committee members, help from advisor, and support from my father Zahir Shah.

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Abstract of Thesis

Traffic Operation and Control during Evacuation Conditions: An Integrated Management System with Multi-level Coordination

During the past decade, large storms, mudflows, hurricanes, floods, and many other extreme conditions have caused massive economic and human losses in cities and regions around the world. In the United States, Hurricane Katrina and the September 11th, Terrorists Attacks are relevant examples of such conditions where explicit cost-benefit analyses showed that by presenting a systematic and efficient evacuation scheme in response to such hazards, people lives can be preserved at a much lower cost.

Evacuation study is a complex subject that mainly includes (1) a demand side, (2) a network supply side, (3) a control side and (4) a behavioral side. Focusing on the control side of the problem, the objective of this thesis is to offer a dynamic integrated control strategy that can respond in real-time to any change in demand and supply during extreme conditions. Given the complexity of the problem, a simulation based model is required to get a better understanding and analysis of the process at hand. Through the use of the dominant path concept and transforming the evacuation problem into multiple corridor-based evacuation problems, the corridors where lanes can be reversed and where "intelligent" control tools can be deployed are better assessed. Evaluating evacuation in such framework allows the integration of real-time control strategies into the problem; the demand aspect (specification of the safe versus unsafe zones) and the complexities related to the dynamic assignment of evacuees to different routes are better captured: the model can integrate multiple data sources and network-level traffic routing while

allowing improved coordinated control strategies (optimal signal timing, use of variable message signs and ramp-metering).

The logic adopted to realize the objective above is a reactive integrated control. A control "optimal" module mainly includes VMS, path-based coordinated signals and ramp metering control strategies; this module is integrated into a dynamic simulation-assignment framework. A base case simulation using the "every-day" origin-destination demand pattern allows determining the network-wide performance measures including the experienced delays and travel-times. Once determined and with the knowledge of the regions to be evacuated, the highest number of impacted vehicles (traveling to, from or through the impacted areas) and the corresponding dominant paths are identified. Accordingly, coordinating between the controls strategies along these paths (corridors) allows a faster and smoother evacuation. After identifying the components of the above control "optimization" logic, the formulated method is tested on a portion of the Maryland CHART network, USA. The portion considered consists of the I-95 corridor network between Washington, D.C. and Baltimore. The impacted area to be evacuated is inside the capital beltway (i.e. Washington DC) and the safe area to be reached is along the path towards Baltimore. The network is bounded by I-695 in the north, I-495 in the south, US 29 to the west and I-295 to the east. The network includes four main freeways (I-95, I-295, I-495 and I-695), as well as two main arterials (US29 and Route 1). The Maryland CHART network reduces to 2182 nodes, 3387 links and 111 zones.

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List of Abbreviation

No.	Page
1. VMS: Variable Message Sign	vi
2. CHART: Coordinated Highways Action Response Team	vi
3. CTM: Cell Transmission Model	8
4. ITS: Intelligent Transportation System	9
5. CPM: Critical Path Method	14
6. ICM: Integrated Corridor Management	17
7. DOT: Department Of Transportation	17
8. MOE: Measures Of Effectiveness	19
9. IRZ: Immediate Response Zone	22
10. ODE: One Destination Evacuation	25
11. ODE: One Destination Evacuation	25
12. ATIS: Advanced Traveler Information System	51
13. O-D: Origin Destination	52
14. GUI: Graphical User Interface	55
15. TAZ: Traffic Analysis Zone	63
16. HOV: High-Occupancy Vehicles	63

CHAPTER 1- EVACUATION CONDITIONS

1.1. Introduction and Motivation

During the past decades, large storms, mudslides, hurricanes, wild fires, floods, and many other extreme events have caused massive economic, human and social losses. In United States, the motivation for carrying this research is based on the frequency and the severity of extreme events that impacted a variety of areas and states with a demand to more effective evacuation processes. Hurricane Katrina hitting the states of Florida and Louisiana in 2004, and the New York terrorists attack on September the 11th of 2001, is among the most severe examples of such conditions. With better media coverage, the public is learning the extent of damages occurring increasingly in large population centers (Mclaughlin, 2006). These centers are subjected to higher natural risks (i.e. global warming) and man-made disasters/attacks (i.e. terrorist attacks against political and/or financial hubs). Explicit cost-benefit analyses show that by accepting evacuation as an optional/mandatory response to such events, human and material losses can be reduced at a lower cost (Shekar and Kim, 2006). Accordingly, the research community has been interested in understanding and developing this possible solution: a fast, effective and economical evacuation.

As mentioned above, evacuation or extreme conditions can be caused by both: human actions and/or natural events, which require a system by which the effected people and residents can be transferred to safer locations. Accordingly, this study describes the appropriate control methods by which people can be evacuated from an impacted area to the nearest safe area in a safe and efficient manner. Efficient evacuation is currently subject of research of major priority due to increasing risks and the corresponding diversity and wide impact while involving different disciplines and areas of specialty. Such disciplines include but are not limited to psychology/sociology (Brunsma et al., 2007), operational management/military (Davis et al., 2007), theology, science/biology (Horne, 2008), and engineering/transportation (Russo and Vitetta, 2002: Chen et al., 2007). For transportation system planners, one of the main issues has been traffic jams and congestions during the evacuation process. As additional research can be performed on such topics, this thesis mainly focuses on the control techniques that contribute to the reduction of traffic congestions during the evacuation processes.

An example of research already performed on this topic from the transportation perspective, is the work of (Shekhar and Kim, 2006), which describes the contra-flow transportation network reconfiguration for evacuation route planning. “Contra-flow or lane reversals have been discussed as a potential remedy to solve such tremendous congestion by increasing outbound evacuation route capacity” (Shekhar and Kim, 2006). Shaker and Kim’s research also concluded that although contra-flow is primarily important for evacuations, its applications are not limited to emergencies, the two center lanes of different major arterials in the Washington, D.C. Metropolitan Area (i.e., Connecticut Avenue, NW, DC, Georgia Avenue, Maryland etc) are used in a reverse lane fashion to efficiently control capacity for morning and evening commuter peak time.

In this chapter, evacuation conditions and four different aspects of this complex process have been defined. This study focuses on the safe evacuation by reducing traffic congestions and thus saving the “travel/trip time”, which results in a faster, safer, and more efficient evacuation process. The next section describes the four aspects of the evacuation study.

As a summary, the main objective of this paper is to address different control strategies need to be coordinated for a more efficient evacuation. Moreover, this research work offers a dynamic integrated control strategy that can respond in real-time to any changes in demand and supply flows during extreme conditions. For additional clarification in this chapter, the control methods involved in the proposed strategy are ramp-metering, contra-flows, variable message signs, and signal controls. In addition to the control aspect of the evacuation, this thesis also describes other aspects of the evacuation study such as demand, nature of extreme events, and stochastic simulation/traffic assignment. The following section presents an extreme events classification scheme. Section 1.3 describes the objective and scope of this research study. Section 1.4 briefly discusses the framework and the methodology of the research before concluding with the problem statement in Section 1.5.

1.2. Evacuation Conditions: A Classification Scheme and Transportation Approach

Evacuation conditions or Extreme conditions are basically the conditions, in which there is an increase in the danger threshold in a given location threatening the corresponding residents/goods thus encouraging an optional or mandatory change of the allocation of recourses. In the transportation field, this change in the allocation of recourses and the re-location of goods and people is what researchers call: evacuation. In this research, extreme conditions are seen as either human-caused or naturally-caused while requiring a system by which all the affected people and residents can be transferred to safer “zones”. Table 1.1 shows the sub classifications of these two classes of extreme events.

Nature-Caused Evacuation Conditions	Human-Caused Evacuation Conditions
Hurricanes	Terrorist Attacks (e.g.. September 11th, 2001)
Snow Storms	War Conditions
Floods	Fire
Volcano Eruptions	Electricity
Earthquakes	Use of Nuclear Materials
Heavy Rain	Bombing

Table 1.1: Sub Classifications for the Nature-Caused and Human-Caused Evacuation Conditions (Hamdar, 2004)

The above two types of extreme conditions shown in the table have some similarities; however they differ in terms of a) predictability, b) threatening or danger level, c) degree of urgency, and the possibility of controlling them (Hamdar, 2004). Terrorist attacks, war, use of nuclear materials, and bombings are few examples of human-caused extreme conditions. While hurricanes, snow storms, floods, earthquakes etc, on the other hand are considered as natural disasters. In addition, some extreme conditions are considered as a combination of different extreme conditions, such as war: which includes bombing and use of nuclear materials. Moreover, different extreme conditions have different threatening or danger level. Heavy rain, high flood, and high intensity earthquakes, for example, are more extreme than others. In general, any extraordinary conditions (nature-caused or human caused) that effect the transportation system are known as extreme conditions.

As mentioned before, extreme conditions are different in terms of urgency, predictability, and the ability to control the consequences. Hamdar in his research states: "the degree of urgency in evacuation is characterized as high, moderate or low. The urgency increases with the extent to which a given situation maybe life-threatening. Control measures are characterized by the extent to which consequences can be contained and confined to a given bound area, and by the availability of direct actions that may reduce negative impacts. For example, hurricanes cannot be or contained within a given area, and thus the control measures are given a "low" designation. Similarly, while heavy rain cannot be limited or confined within a given area, its effects can be mitigated by a number of measures like better draining and lighting roads for better visibility. However, this dimension for characterizing extreme conditions is admittedly problematic; for example, war may involve a wide range of destructive tools, from nuclear weapons to conventional grenades, and is considered here as having only moderate control measures", (Hamdar, 2004).

Some extreme conditions occur independently, while the others jointly with other extreme conditions. Accordingly, one extreme condition can be the result of another extreme condition. Flood, for instance, are caused due to heavy rain. Therefore, these extreme conditions do not have certain boundaries.

In this thesis, the focus on extreme conditions involves the fact that human life is highly threatened by it and to which high degree of urgency, evacuation is required. Accordingly, this study focuses on extreme conditions in terms of traffic and transportation mode.

Based on the above classification scheme, transportation specialist' main concern has been traffic jams and congestion during the evacuation process. From a traffic engineering standpoint, this study describes an appropriate control coordination method assisting in evacuating drivers from an impacted area while alleviating congestion due to the change in demand patterns.

To better illustrate the problem and explain the corresponding research, the evacuation scenario is seen from four different transportation perspectives:

1) a control perspective,
2) a demand perspective,
3) a traffic assignment perspective,
4) and a driver behavioral perspective.

The following subsections present the boundaries of each perspective and the method by which the proposed research addresses them.

1) CONTROL PERSPECTIVE

The control side mainly tackles the traffic operations and controls due to which the greatest number of people and vehicles would be allowed to leave an extreme event impacted area and transferred to safer zones in the shortest "clearance time" possible. This study focuses on four main traffic controls (ramp metering, signalization, variable message signs-VMS, and contra-flow operations). The need is to offer the method by which these control strategies are to be changed to give priority to evacuees and the corresponding coordination scheme.

2) DEMAND PERSPECTIVE

The demand side studies the method by which the demand should be loaded on a network as well as the destinations to which the evacuees should be sent. Assuming these origins and destinations are fixed and known, the objective of this research work is to offer a dynamic integrated control strategy that can respond in real time to changes in demand and supply for vehicles already in the network during the extreme event. Accordingly, complexities related to the dynamic assignments of evacuees to different routes/paths are to be addressed in a simplistic manner: use of VMS.

3) TRAFFIC ASSIGNMENT PERSPECTIVE

This aspect of the evacuation focuses on the "quasi-optimization" side, which focuses on the routing problem where the "optimal" paths are to be found minimizing the travel time and risk experienced. This study uses a dynamic simulation tool to realize such objective.

4) BEHAVIORAL PERSPECTIVE

Since human behavioral under emergency conditions may be different from day-to-day travel patterns, the driver behavior and the evacuees response to a threatening event-are important factors to be considered, while modeling or running a simulation. Even though some literature addressed this issue qualitatively (Hamdar, 2004), this thesis does not tackle this problem assuming that the flow-density relationship in every-day conditions apply in extreme events.

Even though contributing in the different sides of the problem, this thesis focuses on the control side. Earlier related research focused on studying the use of contra-flow or lane reversal method. As mentioned in the previous subsection, "contra-flow operations aim at increasing the capacity of the available network by reversing the direction of inbound lanes to the impacted areas to outbound lanes to the safe areas (safe zones). One of the latest studies in this domain assessed the benefits of the use of contra-flows via use of macroscopic (cell transmission model CTM) and microscopic (VISSIM Model) models." (Dixit et al., 2008). The simulation models helped identifying the locations for accessing the contra-flow lanes from normal lanes (crossovers) on the I-4 freeway between the Tampa and Orlando in Florida.

"Today, 11 of the 18 coastal states in the United States frequently threatened by hurricanes consider the use of contra-flow as part of their evacuation strategy." (Wolshon et al., 2002). “The contra-flow problem for evacuation can be defined as follows. A transportation network is given with multiple sources and destinations. Each source has initial occupancy. Each directed road segment connecting two nodes has capacity and travel time. Researchers are interested in finding a reconfigured network identifying the ideal direction for each edge to minimize evacuation time by reallocating the available capacity suing lane reversals.” (Shekhar and Kim, 2006). However, existing work concluded that finding the optimal contra-flow network configuration is considerably challenging because it requires enumerating the combinations of edges (i.e., road segment) and their directions, while, comparing those by calculating evacuation time. “The difficulty originates from the combinatorial nature of the problem.”, (Shekhar and Kim, 2006). This challenge drove the author to tackle the contra-flow problem in a simplistic manner focusing on pre-determined routes where lane reversals can be performed in a near-real-time manner.

Other than lane reversal, the latest technological developments have triggered researchers to analyze the importance of intelligent transportation systems (ITS) in evacuation scenarios. Wireless traffic sensors, processed camera recordings, incident detection devices, weather sensors, dynamic message signs and highway advisory communication systems are considered to be of great use for a smoother, faster, and safer evacuation.

Based on the above, the author focused on the coordination scheme of the suggested control operational devices motivated by the fact that re-routed drivers tend to follow a set of dominant paths.

1.3. Objective and Approach

The main objective of this study is to provide a feasible control strategy for a more efficient evacuation. Accordingly, for added fidelity, the thesis aims to offer a dynamic integrated control operational plan that can respond in real time to changes in demand and supply flows during extreme events. The considerable dynamically coordinated control methods are ramp metering, contra-flows, variable message signs, and signal controls.

“Through the use of the dominant path concept and transforming the evacuation problem into multiple corridor-based evacuation problems, the corridors where lanes are to be reversed and the intelligent tools to be employed on such corridors can be better assessed. Evaluating evacuation in such framework allows the integration of real-time control into the problem; the demand aspect (specification of safe VS unsafe zones) and the complexities related to dynamic assignments of evacuees to different routes/paths are better integrated: the model takes into account multiple data source integration and network-level traffic routing while allowing the improvement of the developed control strategy.”, (Hamdar et al., 2010).

Accordingly, this study aims at finding coordination between the control strategies along these paths (corridors) to allow a faster and smoother evacuation. After identifying the components of the above control “optimization” logic, the formulated method is tested via simulation on a portion of the Maryland CHART network, USA. This modeling and simulation approach is validated through the use of output measures of effectiveness. For that, the portion considered consists of the I-95 corridor network between Washington, D.C. and Baltimore. The impacted area to be evacuated is parts of the Washington DC area and the rural less congested safe area to be reached is along the routes between the city of Washington DC and the city of Baltimore. The network is bounded by I-695 in the north, I-495 in the south, US 29 to the west and I-295 to the east. The network includes four main freeways (I-95, I-295, I-495 and I-695), as well as two main arterials (US29 and Route 1). The Maryland CHART network reduces to 2182 nodes, 3387 links and 111 zones.

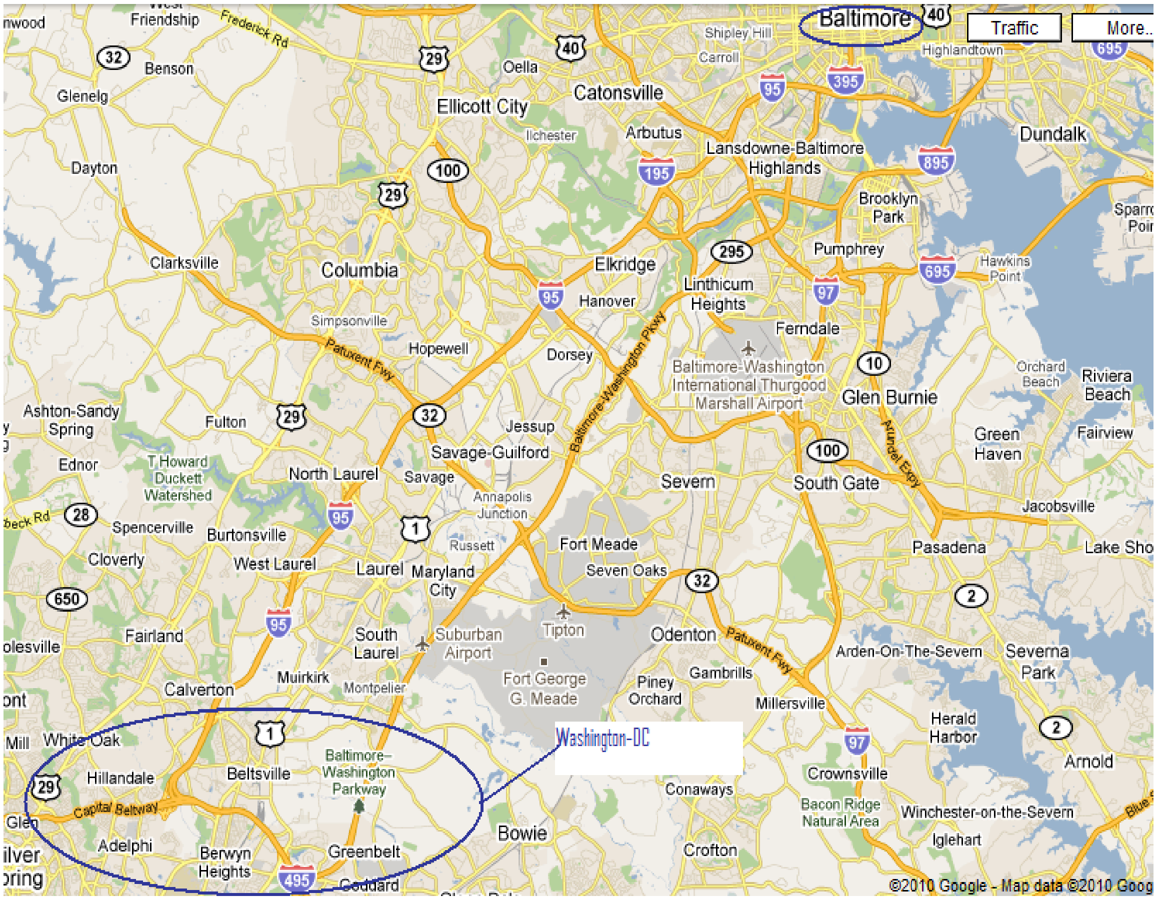


Figure 1.1: Map of the Study Region (Google Maps, 2010)

1.4. Framework and Methodology

The logic adopted to realize the objective above is a reactive integrated control logic, which includes VMS, Contra-flow, path-based coordinated signals and ramp metering control strategies; this module is integrated into a dynamic simulation-assignment framework. A base case simulation using the every-day origin-destination demand pattern allows determining the network-wide performance measures including the experienced delays and travel times. As we know the region needed to be evacuated, the vehicle impacted (to, from or through the impacted areas) and the corresponding dominant paths. Accordingly, the objective is transformed to finding proper coordination between the control strategies along these paths (corridors) to allow a faster and smoother evacuation. It should be noted that the coordination scheme will be found dynamically using a control optimization module based on a reactive control strategy. The key component of this control system is to identify the dominant paths. The dominant path is known to attract a higher number of vehicles when there is capacity reduction on other routes. These vehicles will be seeking for alternative routes that minimize their individual travel time. However, when more vehicles change their routes using the dominant path, the links along this path will reach capacity and control strategies will be needed to coordinate their corresponding traffic movement.

1.5. Contributions of this thesis

The primary goal of this study is to provide a feasible control strategy for a faster and efficient evacuation. The dynamically coordinated control methods are ramp metering, contra-flows, variable message signs, and signals controls. Accordingly, the aim is to offer a dynamic integrated control operational plan, so that it can respond to any change in demand and supply flows during evacuation events.

The key component of the coordination of the control strategies is to identify the dominant paths. A dominant path is a path that attracts the highest number of vehicles. During any scenario, since more vehicles change their routes in order to use the dominant paths and thus increasing number. of vehicles on them. Accordingly this research will aim to install control strategies on those paths in such a way to coordinate their corresponding traffic movement.

During evacuation conditions drivers from the impacted areas are required to drive to the safe zones and which cause the increase in the trip generations towards the safe area. This study aims to perform such demand patterns through the use of variable message signs with the calibrated degrees of drivers' responsiveness.

By realizing the above objective and through reviewing the latest work on this subject, the following contributions are expected from this thesis.

- Coordination of control strategies (dominant paths)
- Integration of the control coordination with a dynamic simulation framework (dynamic route assignment use with demand loading pattern through one dynamic simulation tool)

- Practicality of the model to apply in real time via simplistic and readily existing technologies: simple contra-flow method, existing single time logic, VMS to shift demand, existing widely used ramp metering technique.

Finally, this thesis describes the dominant paths concepts with explaining the details of the critical path technique. The critical path technique is a “key” to the operational traffic related strategies for any nodal network and serves as a base for this research: the critical paths are claimed to include the quickest routes to be followed in the evacuation. Thus, dealing with traffic through Critical Path Method (CPM), an improved evacuation concept is introduced on the road networks as is the case in the formulation explained in chapter 3.

1.5. Problem Statement

This thesis examines the effects of extreme conditions on the impacted area and vehicles and thus the congested traffic when all the vehicles move from impacted area to safe area. An area is facing extreme conditions because of natural or man-made related activities, and threatened vehicles in that area need to be transported to the nearest safe area or zone. In this regard, the most appropriate and shortest paths would be chosen so that the impacted vehicles reach safe zone in the less possible time. Since all the impacted vehicles will be going to the safe zone possibly leading to traffic related problems (congestion). The main focus is to transport the impacted vehicles from impacted area to the safe zone in finding better alternatives routes by minimizing the corresponding conflicting volumes through the use of control. In doing so, the following measures would be taken:

1) Identification of the dominant paths (that attracts most traffic).
2) Recording the critical paths.
3) Installing the traffic control devices on the critical paths.

Due to heavy traffic on the critical paths, control measures and devices would be installed and coordinated in such manner, so that the travel time can be reduced.

In summary, this chapter presents the introduction, objective, framework, and problem statement of our study. The following chapter (Chapter 2) summarizes the different relevant literature published in this field of study, which help in our model formulation. Chapter 3 explains the model formulation and the corresponding technical details. Chapter 4 presents the experimental set-up, the software used and the model, calibration and validation. Chapter 5 describes the numerical results obtained from the tired simulation scenario and the corresponding analysis/insights. Finally Chapter 6 presents the concluding remarks and the future research needs.

CHAPTER 2 - LITERATURE REVIEW

2.1. Research Approaches

Evacuation study covers a wide range of subjects and special situations. As discussed in Chapter 1, this thesis aims at finding an integrated management system with multi-level coordination to respond to different sides of the evacuation problem. Translating this objective to the literature review, this chapter mainly includes the following four transportation approaches.

1) Control Aspect
2) Demand Aspect
3) Network Supply Side/Assignment Aspect
4) Driver Behavioral Side

Previous papers and researches in the four aspects, mainly focusing on control aspect, of this complex study of evacuation have been reviewed. The following is the literature review explaining the past researches related to the evacuation-with the corresponding assessment. Each category is evaluated with respect to its suitability to our study thus helping in the model formulation.

2.1.1. Control Aspect

The evacuation control side constitutes the base of the thesis: the literature relevant to the integration and adaptation of the control and operational strategies for a corridor of network in order to have a smooth and fast traffic flow during extreme conditions is needed. The first work of interest is based on (Hamdar et al., 2005), explaining the concept of the Integrated Corridor Management (ICM), which is introduced by US DOT. One of the ICM initiative’s objectives is the coordination between the operations of the individual network facilities in order to have a continuous traffic without congestion. This objective involved both safety considerations and mobility considerations. In order to evaluate the operational strategies for ICM, a dynamic simulation program was used. Special focus was given to the short-term optional strategies, their effectiveness to support the decision making system and the cost of their implementation on a road network system, which includes information provision cost and control adjustment cost. Two relative analyses were carried out on the portion of the Maryland CHART network: a) a work zone analysis and b) an incident analysis. In the work zone analysis, best results were obtained when a strategy of simultaneous implementation of signal coordination, advisory warning VMS and optional detour was followed. In this way, time required for traffic flow can be minimized. This study also suggests that the use of path-based signal coordination could be an effective ICM strategy. On the other hand, in the incident analysis, the best result is obtained when the VMS are activated only during the incident duration of time and when the warning is provided to the vehicles approaching the incident. This paper helped in picking the right strategy and how the management strategies should be combined together and also to implement it on our selected road network. This is a platform for our study, which means both the strategies for work zone and incident, is combined in an appropriate way while allocating effort to the demand side, in order to have smoother traffic flow time during extreme conditions. The short comings of this presented paper are: 1) it did not focused on the long-term operational highway management strategies such as demand management, and 2) the method adopted is static, and 3) it does describe the dominant paths concept generally without explaining the details of the critical path technique.

On the other hand, this thesis takes into consideration the concept of contra-flow or lane reversals to reduce the traffic congestion during evacuation. The corresponding literature review shows that this control technique has been discussed, as a potential remedy to solve tremendous congestion during evacuation process by increasing the outbound route capacity. (Shekar et al., 2006) defines the contra-flow network reconfiguration problem by assigning source nodes with evacuees and destination nodes. This approach, gives an “ideal” direction for each edge so that evacuation time can be minimized. Combining the edge (road segments) directions and comparing them by calculating the corresponding evacuation time is performed while a complete enumeration leads to the finding of the optimal contra-flow network configuration. The difficulty of this method lied in the fact that this problem was combinatorial in nature. In other words, the contra-flow problem was approached by mathematical optimization, which showed scalability limitation.

Another shortcoming related to contra-flow operations is the access to the contra-flow lanes. These accesses are referred to as crossovers. The placement of crossovers in an inappropriate location might result in bottlenecks, which adversely affect evacuation operations. That is the reason why, the appropriate positions of crossovers are so important for any evacuation process dealing with control strategies. In addition to the fact that inappropriate positions of the crossovers would affect the efficiency of evacuation, sometime it is also constraint by the economical factor, which is explained in a very detailed manner by (Dixit et al., 2008). Thus, this paper was very helpful in our study for identifying the crossovers and placing them in appropriate places. This study tested four different strategies with different crossover locations on Interstate 4 (I-4) evacuation route from Tampa to Orlando, Florida and compares two levels of simulations (Mesoscopic and Microscopic, represented by CTM and VISSIM). These two simulations were used in order to have the best crossover locations for I-4 route. After simulation, it was found that provision of the first crossover after Tampa City and second after the Plant City provided best results. But, on the other hand those results were slightly better than the placement of one crossover after Tampa. Thus, after taking in to account the economical factor, it was decided to locate one crossover after Tampa. By looking into other alternatives, later it was also concluded that to locate less number of crossovers in appropriate positions is better than to have more crossovers located on inappropriate positions. This paper also found that CTM predicted the MOEs as well as VISSIM did, with an approximately 5% error in the results between CTM and VISSIM. With it faster computing time, CTM was ideal for use as a real-time decision support system and would be able to determine dynamic crossovers in the event of bottlenecks caused by incidents or vehicle breakdowns. The fast computation and realistic representation of traffic flow make it suitable for use for the modeling of evacuation routes and quick verification of the effectiveness of evacuation plans. CTM is able to dissipate all vehicles into the network, allowing more holistic comparison of the various strategies. With the need for more flexible evacuation plans, CTM`s capability makes it an ideal tool for use in testing of various scenarios

Learning from such literature, this thesis adopts a different "solution of contra-flow network reconfiguration by taking in to account the road capacity constraints, multiple sources, congestion factor, and scalability. In order to classify the computational structure of the contra-flow reconfiguration problem by the ratio of the number of evacuees to the bottleneck capacity of the transportation network, a notion of overload degree has been introduced", (Dixit et al., 2008). The contra-flow routes are thus assigned based on the over-load degree (i.e., presence along the critical paths) and the practicality in changing the flow for real-time dynamic response. As for the second contra-flow related shortcoming, the positions of crossovers are pre-provided based on the practicality of shifting the traffic directions with special focus on major roads/freeways. Finally, a mesoscopic simulation tool was used for added fidelity (vehicle trajectory detection) and faster computation.

The dominant path concept was used by (Abdelghany et al., 1999), while looking into the paths which attracts highest number of vehicles, when there is capacity reduction on other routes. Using such definition along with the contra-flow or lane reversal concept, a control strategy can be dynamically into the problem. This integration scheme has been realized through an optimization module (dominant path module) initiating a reactive control modul. It should be noted that, this thesis focuses on evacuation with a need to take into account several control strategies simultaneously in addition to the demand-supply side of the problem.

Our researched assumed an emergency situation in the urban area of Washington, D.C and the safe area to be in a more rural area along the road to Baltimore, MD. One of the freeways chosen for the evacuation from Washington, D.C is the Interstate 95 (I-95). In order to achieve this scenario, there should be some traffic strategies which control and link the urban traffic with the freeway traffic via freeway ramps. (Kwon et al,. 2005), describes such kind of situation by evaluating the effectiveness of the alternative strategies for evacuating the traffic in downtown Minneapolis, Minnesota. This included the evacuation of a sellout crowd in the Metro dome. In such case-study, the southwest portion of the Twin Cities metro area was selected as the network portion of interstate. "The simulation results showed that the traffic conditions at the outbound links of the freeway and the access capacity from downtown to the freeway are the critical factors. In other words, the evacuation time can be decreased if the capacity on the freeway ramps is increased. This research used the Dynasmart-P software for simulating the downtown traffic in a large urban network. The hypothetical emergency situation modeled in this study assumes that because of an emergency situation, the evacuation of the entire downtown traffic starts at 5 PM on a normal weekday afternoon (Peak Hours). In terms of the network configuration, following configurations were modeled and evaluation with the Dynasmart:

(i) Only the arterial links and freeway exit ramps approaching the downtown area are blocked when evacuation starts.

(ii) In addition to the configuration (i), the incoming freeway links located inside the network are blocked to prevent vehicles from approaching the evacuation area.

In addition to the configuration (ii), all the inbound-outbound freeway links in the inside network are converted to one-way outbound links, that is, contra-flow", (Kwon et al,. 2005).

The main shortcoming of this study is its assumption of not having any traffic inflow (demand) to the impacted area from the time, evacuation starts. Moreover, the estimation of the evacuation demand under dynamically changing environment is another important issue to be addressed.

2.2.2. Demand Aspect

The objective of this thesis to offer a dynamic integrated control strategy that can respond to changes in demand and supply during the extreme events. In order to achieve such objective, information regarding the methods by which the demand should be loaded on a network (scheduling) as well as the destinations to which the evacuees should be sent to is needed: a literature review on the demand side of the evacuation problem is provided next.

In September of 2005, over one million residents evacuated from the greater Houston area in response to the Hurricane Rita, causing severe congestion on the region`s highways. Lam (Lam et al.,), described the work of Houston-Galveston Area council (H-GAC) with Texas Transportation Institute (TTI) to develop an evacuation model capable of replicating the Rita event and evaluating future evacuation scenarios. For this purpose, a dynamic mesoscopic traffic assignment model was used to simulate two different kinds of traffic simultaneously: the evacuated traffic and the traffic related to the background travel demands. “The main goal of this model was to evaluate different evacuation scenarios numerically, given various demands and strategies. The evacuation criteria was delay, length of queuing, travel time to exit the region, and through volumes getting out of the region. The model had the ability in modeling managed departure and contra-flow lanes. The mesoscopic traffic assignment used in this study works in the following manner. If the traffic demand is below the capacity and the downstream link is clear, the travel time is determined solely by volume-delay function. If the incoming vehicle demands exceed the capacity, the overflow vehicles are blocked at the upstream links and wait until the downstream vehicles have been dispatched. Thus by enforcing the capacity limit, this model estimates more realistic travel time, delay, and volumes than the static assignment”, (Lam et al.,).

This project may have been more efficient, if the network data would have been used more extensively for validation reasons. After reviewing this corresponding paper, the following lessons can be learned.

(i) "Check the entire network coding and implementation, especially in the congested areas and bottlenecks. Make sure the auxiliary lanes and turn lanes are included in the network coding.

(ii) Identify areas in the static model where the demands are over supply.

(iii)Collect hourly traffic count or survey data for creating or to updating hourly split factors.

(iv)Collect hourly traffic count and speed data for validation.

(v) Collect signal information such as optimization or synchronization plan", (Lam et al.,).

Based on the above lessons, heavy and time-consuming data collection challenges maybe faced. In this thesis, there is rather a focus on the modeling and the implementation/validation parts of the problem.

"In the conventional evacuation planning process, evacuees are assigned to some fixed pre-specified destinations mainly based on the geographical proximity. However, adopting such conventional planning process for evacuation, most often results in a low efficient evacuation because of uncertain road conditions, traffic congestions, and road blockage etc", (Yaun et al., 2006). F. Yaun suggests relaxing the constraint of assigning evacuees to pre-specified destinations (Yaun et al., 2006), “a One Destination Evacuation (ODE) concept has the potential to improve evacuation efficiency greatly. According to the authors, the ODE concept can be used to obtain an optimal destination and route assignment by solving a one-destination (1D) traffic assignment problem on a modified network representation. This framework could be feasibly implemented and the efficiency can be increased by allowing evacuees for destinations, before integrating all destinations to a single destination (1D).

In their study, Yaun and Han recognized the fact that models based on a fixed O-D tables, can be quite inefficient when a destination becomes hard or even impossible to access because of congestion or blockage. In such conditions, providing flexibility to the evacuees to head for alternative exit routes and destinations was explored. In their paper, the region to be evacuated is called immediate response zone (IRZ) and traffic destination distribution and route assignment were optimized simultaneously on basis of the concept of one-destination evacuation (ODE). For a road network within an IRZ, *m* origins and *n* destinations were used. This network was modified and augmented to one common destination point. With this modification, a two-step decision-making process for the original evacuation network, including a demand distribution problem and a traffic assignment problem with *m* origins and *n* destinations (*m-to-n assignment*), was translated into a one-step decision-making process for the modified network, which was a traffic assignment problem with *m* origins and *n* destinations (*m-to-1 assignment*). A case study of real-world evacuation operations was selected to demonstrate the feasibility of the proposed ODE model. The area selected for this was Knox County, Tennessee, which had a population of around 382,000. Evacuation of the entire Knox County was modeled. Two network setups or modeling strategies, *nD* and 1*D,* were simulated and compared for their effectiveness. The concluding results showed that the proposed 1*D* method presented a substantial improvement over the conventional n*D* model for both planning and operational purposes: for example, a nearly 80% reduction in the overall evacuation time could be achieved when traffic routing was modeled with en route information in 1*D* framework, and the 1*D* optimization results could also be used to improve the planning O-D table, resulting in 70% reduction in the overall evacuation time", (Yaun et al., 2006).

All these results demonstrated that 1*D* modeling is an efficient method of reducing the evacuation time by providing flexibility in route selection and also in the destinations selection. More importantly, this framework can be implemented and the time savings realized just by instructing evacuees to head for a given one destination (derived from the 1*D* model before hand) may be significant. Accordingly, in this thesis, a one-evacuation-destination case study is tried.

The paper included in our literature review (Balakrishna et al.,) presents a simulation-based framework for the modeling of transportation network performance under emergency conditions. "The framework addressed the need of fast evacuation model which can be used to the performance of the network under a wide range of mitigation measures, such as signal priority and the staged release of the evacuation demand. Critical issues, like data collection and evacuation demand estimation, are discussed in the modeling process. For the emergency analysis DynaMIT, a state of the art simulation model based on DTA, is adapted. The results obtained from this model can be used both offline (for planning and training) and online (for real-time management). These results can also provide the decision makers an idea about the clearance time and the severity of a potential evacuation. For instant, if the time required to evacuate takes more than 14 hours instead of 5 hours, then the availability of police would be needed to manually control critical intersections during evacuation. The benefits of DynaMIT-E are demonstrated through a case study based on contra-flow schemes to reduce the evacuation time for the city of Boston.

The base case for the numerical testing consisted of an evacuation of Boston city by using the available freeway capacity in the region. A time-varying demand profile representing the demand to be evacuated from down town Boston was simulated in DynaMIT-E", (Balakrishna et al.,). Dynamic traffic assignment/route choice was adopted.

2.2.3. Network Supply Side/Route Choice

In general, Network Supply can be substantially altered during an emergency. Some of the links may be closed in the network due to incidents, such as floods, chemical spills, and earthquake. Moreover, depending on the response plans in use, some of the main arteries may be operating in contra-flow mode through lane reversals. Main evacuation routes may also be given priority over side streets through changes in traffic signal plans. A model must quickly accommodate to the majority of these changes.

The network supply side of the proposed research focuses on the routing problem where the optimal paths are to be found minimizing the travel time and the risk experienced in the network. In addition, it also addresses the complexities related to the dynamic assignments of evacuees to different routes. In addition, for efficient evacuation, the author did use the routing module to find the critical paths. The model at hand determines the routes that should be taken to minimize the evacuation while determining the shift in the impacted vehicle demand. Accordingly, the routing module is a critical research step prompting detailed literature review on the subject.

Mollaghasemi developed a methodology for modeling a given transportation networks in order to determine the fastest and most effective evacuation strategy in case of a disaster (Mollaghasemi et al.,). The purpose of the corresponding model is to determine the locations from which the emergency response services should be dispatched, the number of vehicles, and the routes they should take in order to have a fast and efficient evacuation during the emergency. The case-study focused on the area surrounding the Orlando International Airport (OIA), in case of a disaster. A state-of-art traffic simulation tool, called Paramics, has been used. “Shortest path algorithms used by the simulator to assign traffic minimize a cost function that can include travel time and other factors that are important for route selection.

The project was accomplished through the following four tasks.

- The first task involved the attainment and manipulation of the traffic data in the OIA area as well as the traffic network.

- The second task involved enhancement and augmentation of the current Paramics model for the OIA area to include an evacuation module for directing traffic from the airport in addition to the emergency response management module to dispatch services to the airport.

- The third task deals with verification and validation.

- The fourth task involves experimentation with various scenarios under a variety of conditions. For example, accidents are simulated by placing speed reductions or traffic logic control on a lane or a group of lanes during the specified time and duration. The model is run using these conditions to determine the best strategy for evacuation in terms of the routes that must be taken in order to minimize response times.

This reviewed paper addresses a very namely topic, particularly after the September 11 attacks. There is an acute need for improved emergency response, traffic handling, and planning. This project helped in diverting our attention to the routing and re-routing of vehicles from the origins to destination" (Mollaghasemi et al.,).

Chen aimed at investigating the effectiveness of the simultaneous and staged evacuation strategies under different road network structures using agent-based simulation (Chan, 2003). Regarding the route choice, this study assumed that all drivers have good knowledge of the area and will follow the shortest path in order to get out of the impacted area. The shortest path here is the route which costs the least time in normal traffic conditions: vehicles originating from same origins and going to same destinations will follow the same path or route. The shortcoming of this study is the assumption, that the shortest path will be adjusted in the case of traffic jam or emergency conditions.

A study by Hobeika and Kim (Hobeika et al., 1998), suggested that the efficiency and the performance of an evacuation operation largely depend upon the network structure and number of vehicles generated in an emergency planning zone. (Lam et al., 1999; Chen et al., 1999; Quiroga, 2000; Russo et al., 2002) A lot of studies regarding road network performance have been conducted under normal conditions. However, few studies, took in to account the traffic demand under emergency situations and addressed the effect of interactions between individuals' driving behaviors in an emergency situation.

As discussed before, a fundamental issue in modeling of evacuation scenarios is route assignment. The route-choice behavior during normal conditions could be different from that during evacuation scenarios. The route choice model in MITSIMLab has been described by (Yang et al., 2000), the travel times used in the route choice model were developed in an iterative framework taking into account different behavioral patterns.

2.2.4. Behavioral side

Since human behavior under emergency conditions may be is different from day-to-day travel patterns, drivers' behavior and the method by which evacuees would respond to an evacuation scenario are important factor order are important factors to be considered. Accordingly, a special attention should be given to the drivers' behavior side and this can be seen in the following review.

Fu attempted simulating “extreme behavior” by developing a corresponding logit model (Fu et al., 2005). However, little research has been made in order to capture driver`s stress and aggression which may increase during evacuation situations. As an illustration, it has been determined that high level of confusion might result while the driver is following contra-flow directions. In another study (Chen et al., 2007), a sensitivity analysis has been performed in order to find the incident rates during evacuation. In doing so, the corresponding authors randomly assumed three levels of incidents (low, medium, and major) on different locations. Such assumption was left invalidated.

Alsnih and Stopher (Alsnih et al., (2004), noted that it is challenging to identify how evacuees would respond to different evacuation orders (recommended or mandatory). Their study also concluded that many households may not follow an evacuation order because of many reasons, like aiming to protect the property and rather prefer staying at home, seeing neighbors not evacuating, and the fact that evacuation is an inconvenience act. How to capture and then to model the above behaviors and attitudes, is a challenge which needs to be explored especially from the social and psychological perspective.

On the other hand, assuming that the capacity and the demand aspects of a transportation network model are tackled properly, determining a) well-accepted safe destination(s) for different evacuees during extreme events is considered problematic. Evacuees should be sent to the nearest, safest, or the farthest destination from the impacted area. According to Southworth and Chin (Southworth et al., 1987) “destination selection can be modeled in the following four ways:

- Evacuees are assumed to exit the impacted area and move to the nearest exit.
- Evacuees will disperse and will not choose similar exits.
- Evacuees will move to the pre-specified destinations.
- Evacuees will move towards the area given the underlying traffic conditions of the network at the time of evacuation", (Southworth et al., 1987).

Based on the above discussion, the procedure of a destination selection might affect the evacuation operations.

On a more microscopic level, Hamdar (2004) examines the effect of extreme conditions on driver's behavior and thus the on vehicle trajectories. The corresponding author also looked into aggregate traffic flow properties in a simplified transportation network. The main objective was to model individual changes in the driving behavior and to capture accordingly the behavior of the "ensemble". In order to achieve this objective, an exploratory micro-simulation model aiming at capturing driver's behavior under extreme condition, has been formulated. Validation using real-life trajectory data was performed. Finally, a sensitivity analysis has been conducted to determine the applicability of the suggested model.

Since, the aim is to model panic behavior individually, microscopic models of driver behavior are considered. Hamdar (2004), initially used Gipps Model to modify so that it can accommodate behavior under extreme conditions by (i) relaxing some constraints in the model, (ii) alerting the structure of the equations in the model, and (iii) changing the values of the input variables of the model, as a way of representing new traffic situations in different freeway locations.

A 2-lane straight freeway segment of length L was used. On this segment, N vehicle were loaded during an interval of time T (simulation time). The vehicles were all identical with the same vehicle length S. The main assumption made is that each driver has a desired Velocity Vn. The following two main conditions are satisfied in this model.

(1) “In a free-flow regime, a vehicle speed should be less than Vn, which is shown in the following relationship.

$$V_n(t+r_n) \le V_n(t) + .25a_n r_n (1-\frac{V_n(t)}{V_n})(0.25+\frac{V_n(t)}{V_n})^{\frac{1}{2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(i)}$$

(2) In congested regimes, the driver of vehicle n must ensure he/she will not crash into the front vehicle:

i.e., $X_{n-1} - S_{N-1} > X_n$, where:

(i) X_{n-1}, is the location of the preceding model n-1.

(ii) S_{N-1}, is the length of this vehicle

(iii) X_n, is the location of the vehicle of interest when it comes to rest after reaching at time $t + r_n$, where r_n, is the reaction time.

After satisfying the above two equations, the details of the Gipps model has been modified by introducing a risk-based parameter D_n. The new model thus represents an attempt to modify Gipp’s car – following rules to capture certain aspects of driver’s behavior under panic conditions. It is complemented with a lane changing model for a more complete elementary representation of traffic interactions in a simple two-lane highway section.

After implementing and simulating of the model, the following driving characteristics were addressed:

(a) decrease of headways.
(b) increase of velocities for aggressive drivers.
(c) higher acceleration and deceleration rates.
(d) and higher velocity variance due to the presence of aggressive drivers", (Hamdar, 2004).

After reviewing the above literature related to the drivers' behavioral side, it would be now easier to conclude that a deep understanding of critical behavioral issues is still needs to be addressed, such as impact of evacuee compliance on the planner's instructions and the panic related cognitive processes. However, this aspect of the problem is considered beyond the scope of this thesis especially with the involvement of microscopic modeling and the related psychological details. These details cannot be captured via mesoscopic simulation. This study instead proposes an integrated optimal evacuation framework that would potentially synergize some of the previously mentioned strategies.

CHAPTER 3 - MODEL FORMULATION

3.1. Introduction: Control Methods

In this chapter, special attention is given to the, traffic control strategies that need to be coordinated during evacuation conditions. After reviewing the existing research performed in chapter 2, while identifying the corresponding shortcomings and areas of contributions, this section presents an improved control alteration model.

The main focus of this thesis is on the control side: to find coordination between the control strategies such as contra-flow use, signal coordination, use of variable message signs and ramp-metering: this coordination is performed through, identifying critical paths, during extreme or evacuation conditions, in order to have an integrated real-time dynamic assignment problem. Details on the above control terms are provided as follows.

3.1.1. Contra-flow

Contra-flow lane reversal refers to plans that change the normal flow of traffic, typically on a controlled-access highway (such as a freeway or motorway), to aid in an emergency evacuation and thus increasing the road capacity for evacuating more vehicles in less time.

3.1.2. Signal Coordination

After determining the dominant paths in a road network, all signals on these paths are coordinated so that to have a smooth and faster evacuation. It should also be noted that signals are coordinated on a dominant path basis in order to have a traffic flow free of blockages at the intersections.

3.1.3. Variable Message Signs

A variable message sign, often abbreviated as VMS, is known as an electronic modifiable traffic sign often used on roadways to give travelers information about special events. Such signs normally warn of traffic congestion, accidents, incidents, roadwork zones, or speed limits on a specific highway segment. In this thesis, VMS are mainly used to control the demand through guiding vehicles to safer zones and diverting vehicles from impacted zones.

3.1.4. Ramp Metering

A ramp meter, ramp signal or metering light is a device, usually a basic traffic light or a two-section signal (red and green only, no yellow) light together with a signal controller, that regulates the flow of traffic entering freeways according to current traffic conditions.

3.2. Model Structure

3.2.1. Dominant Path VS. Critical Path

In a road network, a dominant path is that path which attracts highest number of vehicles, when there is a reduction in capacity in other paths of the network. It is the necessary path or sequence from start to finish, determining the time needed for the travel completion and the longest time consuming path of a road network. As, the objective of this paper is to offer a dynamic integrated control strategy, there is a need to determine such path(s) in a dynamic manner facing the corresponding change in demand and traffic patterns. The demand aspect of the study involves the vehicular demand that should be loaded on a network and also the identification of the origins and the destinations during evacuation conditions. The network supply side deals with the network route choice "optimization" so that to have the "optimal paths" which lesser travel times. The control side integrates and evaluates the control and operational strategies for a corridor of network in order to have a smooth and fast traffic flow during extreme conditions. Finally, the behavioral side describes how evacuees would respond to an evacuation order while they are emergency conditions, which is shown by modeling or running a simulation. The key term linking all of the above aspects is the dominant path component. Having dynamic time-dependent dominant paths changing as the extreme event progresses allows transforming the problem into coordination along these paths as a variable corridors management system. Along the dominant paths, the impacted vehicles are recorded as the vehicles that were heading to, leaving or passing through the impacted zone. The number of these vehicles is recorded dynamically as time progresses through sensors along with the surrounding boundaries and major routes inside the zone of interest. The k paths that show the highest number of such impacted is/are referred to by the critical path(s). At this stage, k is the set to be equal to one. However, in terms of formulation, k can be any integer number where if two critical paths are in conflict, the path with the higher number of impacted vehicles is the path with the higher priority. This higher priority path dictates the approaches along which coordination is needed. The dominant/critical path idea is illustrated in figure 3.1. In this figure, a section of a transportation network is shown in terms of links and nodes. Ramp meters and signalization strategies along this path are shown and between which coordination is needed.

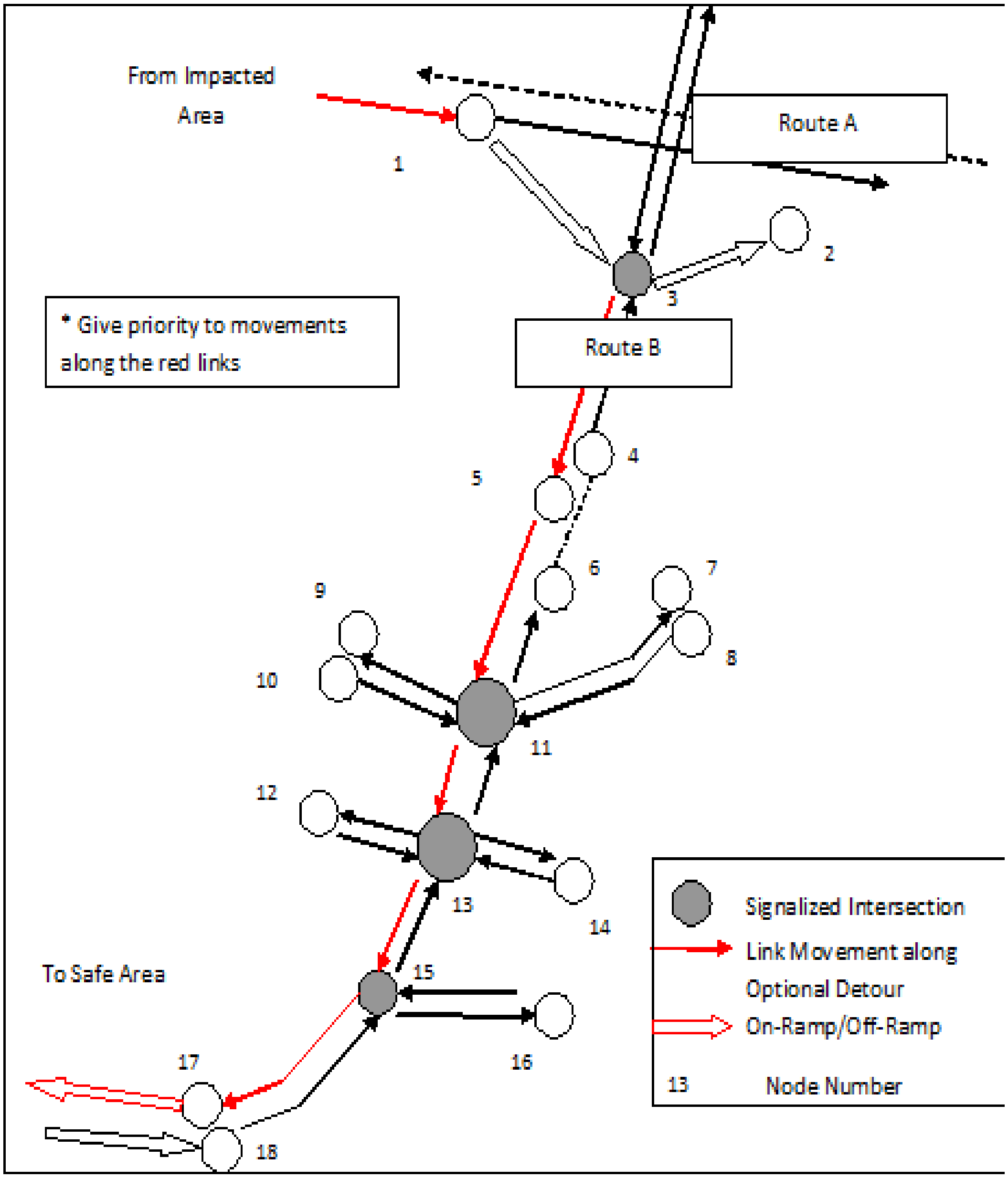


Figure 3.1: A Dominant Path Illustration (Hamdar et al., 2010)

3.2.2. Mathematical Set-Up

The evacuation route planning is a process designed to remove residents from a “dangerous area” to a safer zone as quickly and as safely as possible. It is necessary to represent the situation with a mathematical graph structure. Let G (N, E) be a directed network with N, the set of nodes, and E, the set of links. Each link has an initial capacity and an initial direction. The evacuation situation has one source node and one destination node. We want to find a reconfigured network by Contra-flow with the objective of maximizing the evacuation flow and thus minimizing evacuation time.

Given:

1) A transportation network, a directed graph G (N, E).
2) Each link has a capacity and an initial direction.
3) Source and destination nodes.
4) Transshipment nodes.

Objective:

Maximize the evacuation flow so that the evacuation time can be minimized.

Constraints:

1) Direction of each link can be flipped to allow Contra-flow.
2) Link is the smallest unit of the Contra-flow.

As an illustrative example, following are the assumed link capacities from the origin node to the transshipment nodes.

From/To	A1	A2	A3	A4
O	11	7	2	8

Table 3.1: Assumed Link Capacities from Origin Node to Transshipment Nodes

Following are the assumed link capacities from first set of transshipment nodes to another set of transshipment nodes.

From/To	R1	R2	R3	R4
A1	5	9	6	4
A2	8	7	9	5
A3	4	6	7	8
A4	12	11	9	7

Table 3.2: Assumed Link Capacities from First Set of Transshipment Nodes to another set of Transshipment Nodes

Following are the assumed link capacities from the transshipment nodes to the destination node.

From/To	D
R1	5
R2	4
R3	8
R4	7

Table 3.3: Assumed Link Capacities from Transshipment Nodes to Destination Node

Network Representation

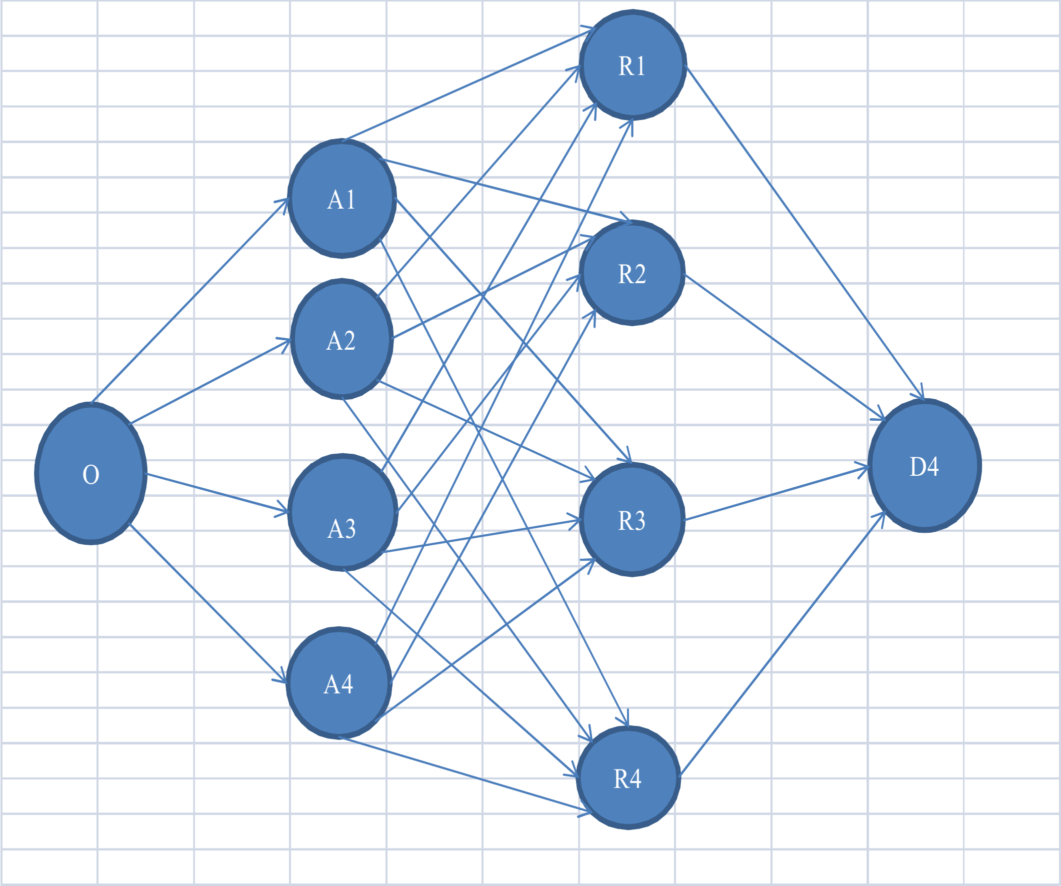


Figure 3.2: Origin, Transshipment, and Destination Nodes Representation

Objective Function

Let X_{ij} be volume of the vehicles that flows between nodes i and j

- Where i= 0, A1, A2, A3, A4
- Where i= R1, R2, R3, R4, D

The objective function is to maximize the flow from the source node.

$$\text{Max} \quad Z= \quad (X_{o\rightarrow A1})+(X_{o\rightarrow A2})+ \quad (X_{o\rightarrow A3})+(X_{o\rightarrow A4})+ \quad (X_{A1\rightarrow R1})+(X_{A1\rightarrow R2})+ (X_{A1\rightarrow R3})+(X_{A1\rightarrow R4})+ \quad (X_{A2\rightarrow R1})+(X_{A2\rightarrow R2})+ \quad (X_{A2\rightarrow R3})+(X_{A2\rightarrow R4})+ \quad (X_{A3\rightarrow R1})+(X_{A3\rightarrow R2})+ (X_{A3\rightarrow R3})+(X_{A3\rightarrow R4})+ \quad (X_{A4\rightarrow R1})+(X_{A4\rightarrow R2})+ \quad (X_{A4\rightarrow R3})+(X_{A4\rightarrow R4})+ \quad (X_{R1\rightarrow D})+(X_{R2\rightarrow D})+ (X_{R3\rightarrow D})+(X_{R4\rightarrow D}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(ii)$$

Node Flow Constraints

- For any given node: ∑Outflow- ∑Inflow = Net Flow
- Case 1: Supply Node, there is no inflow.

  ∑Outflow= Supply (typically unspecified, unconstrained)

- Case 2: Transshipment Node, there are both outflows and inflows, and net flow is zero.

  ∑Outflow- ∑Inflow =0

- Case 3: Demand Node, there is no outflow

  -∑Inflow = -Demand (typically unspecified, unconstrained)

- Hence we only worried about the transshipment nodes.

No negativity Constraints

$X_{i\rightarrow j} \geq 0$ ……………………………………………………………………………(iii)

Where

i= 0, A1, A2, A3, A4

i= R1, R2, R3, R4, D

Solving this problem at every unit time while the vehicles using standard flow density relationships (i.e. modified Greenshield Model used in this thesis (Mahmassami and Sbayti, 2007), the shortest paths are dynamically calculated and while the impacted vehicles are recorded: vehicles are moved at each time step (6 seconds in this thesis) with a link speed V and the new flows are calculated accordingly. This kind of logic need to be connected to the next level of study: the demand level.

3.2.3. A Multi-Level Coordination Scheme

During extreme conditions, long-term equilibrium (user equilibrium and system optimum) does not reflect driver route choice behavior while drivers tend to individually minimize their travel time towards a pre-defined known safe destination. In other words, during evacuation, a reactive “one-shot” dynamic traffic assignment can imitate real-world traffic conditions with higher fidelity.

During an extreme situation requiring evacuating a given impacted area (the new origin), drivers are to drive (directed) to safe zones away from the source of danger. This would occur between times T_1 and T_2 that is during the duration ΔT. Such switch in demand should take into consideration the sudden increase in trips originating from the impacted zone that would not be generated otherwise. These trips can be loaded simultaneously or at phases. Such demand patterns are performed through use of variable message signs with calibrated degrees of drivers' responsiveness (based on the nature and seriousness of the extreme condition). In this thesis, the responsiveness depends on the evacuation urgency with the highest urgency translated into 100% responsiveness.

Once the problem is defined from a demand stand-point, drivers are dynamically assigned to the perceived "shortest" routes. The routes with the highest gains in volumes tend to operate at capacity or over capacity conditions and require the most of attention; these routes attract the highest number of impacted vehicles and form critical paths. As mentioned earlier, the impacted vehicles are vehicles passing through, originating from or heading towards the dangerous zone(s). Different behavioral patterns can be seen. This framework (Figure 3.2) allows identifying the critical paths that should be well identified so that to establish priority in terms of controls movements in a wider multi-level framework.

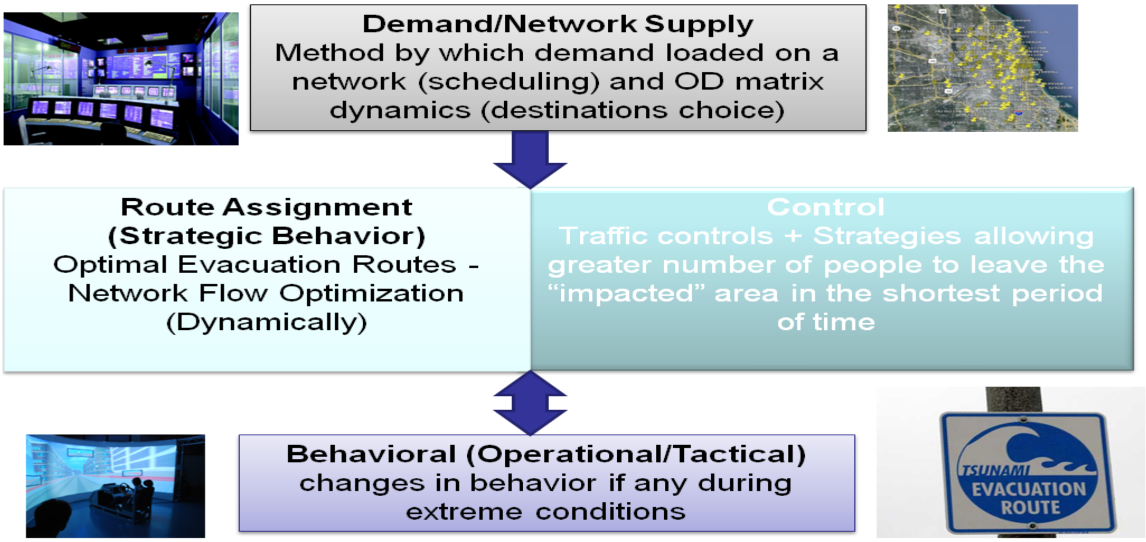


Figure 3.3: Evacuation Framework: a Multi-Leveled Decision Making Process (Hamdar et al., 2010)

In other words, the logic adopted to realize the objective above is reactive integrated control logic; this logic is integrated into a dynamic simulation-assignment framework, which integrates a control optimal module including VMS, contra-flow, path-based signal coordination, and ramp metering control strategies. A base case simulation using the "every-day" origin-destination demand pattern allows determining the network-wide performance measures including the experienced delays and travel-times. Once determined and with the knowledge of the regions to be evacuated, the vehicles impacted (traveling to, from or through the impacted areas) and the corresponding dominant paths are identified. Accordingly, the objective is to find coordination between the control strategies along these paths (corridors) to allow a faster and smoother evacuation. It should be noted again that the coordination scheme is found dynamically using a control optimization module based on a reactive control strategy.

Translating the dominant path concept to the above "solution method", two simulation runs are needed. The first simulation run is with "extreme condition" stand-alone scenario. Once knowing the vehicles impacted, a second run is performed through the usage of warning VMS that provides the best improvement in average trip time for the impacted statistics. The impacted vehicles can be observed either using alternative routes either keeping their original one. Several candidate dominant paths can be identified (Hamdar et al., 2005). Along these paths, the increase of total flows on different links is computed after the use of warning VMS in the DYNASMART_P Software. The link that has the maximum increase in flow is then found. The corresponding path is the dominant path. The characteristics of this solution method are illustrated in figure 3.3.

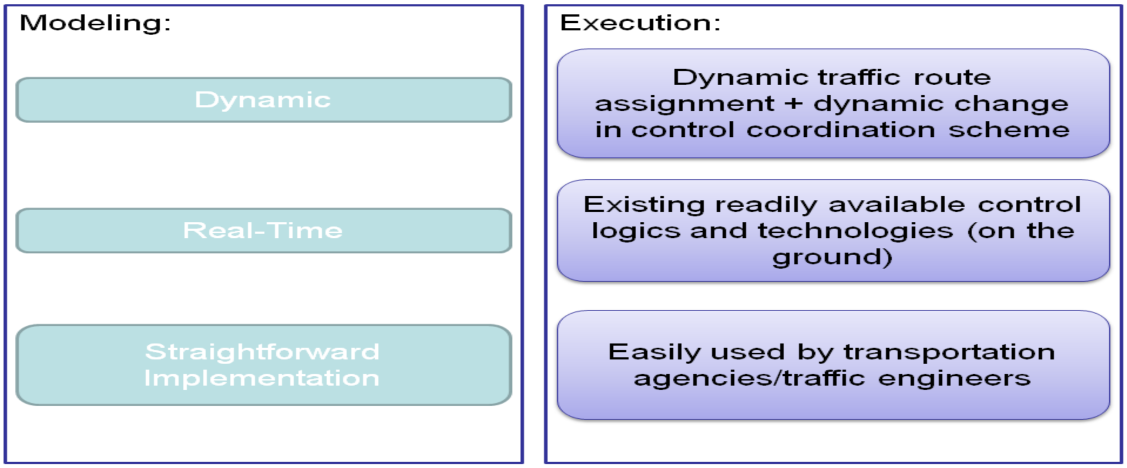


Figure 3.4: Evacuation Characteristics and Approach Adopted in the Paper (Hamdar et al., 2010)

Once identified, the control optimization module is activated: 1) the use of contra-flows along the dominant paths can be assessed first. Pre-determined cross over points are noted without the need for any transportation infrastructure addition/modification. 2) The ramp metering is coordinated along on-ramps on the path of interest and is performed through adjusting the on-ramp flow rates based on the flow and downstream capacity on mainline freeway lanes. The ramp metering logic adopted is that of Papageorgiou's ALINEA (Papageorgiou et al., 1998), with coordination between the feedback-control mechanisms along the on-ramps on the dominant paths. 3) On the other hand, the signal coordination is based on identifying propagation bands for dominant paths and is performed to allow a smoother evacuation scheme. 4) Finally, the variable message signs adopted are of three types: congestion warning message signs, speed advisory message signs and detour (optional or mandatory) message signs. These signs reflect the information provided to drivers and the corresponding responsiveness (Mahmassani and

Sbayti, 1996). The objective of these signs is to avoid clogging and to guide drivers to safe less-congested roads minimizing travel time (within a given allowable periods).

In summary, this formulation (Figure 3.4) can be seen as three mains steps are taken:

1) Identification of the dominant paths (that attracts most traffic).
2) Recording the critical paths.
3) Coordinating the traffic control devices along the critical paths.

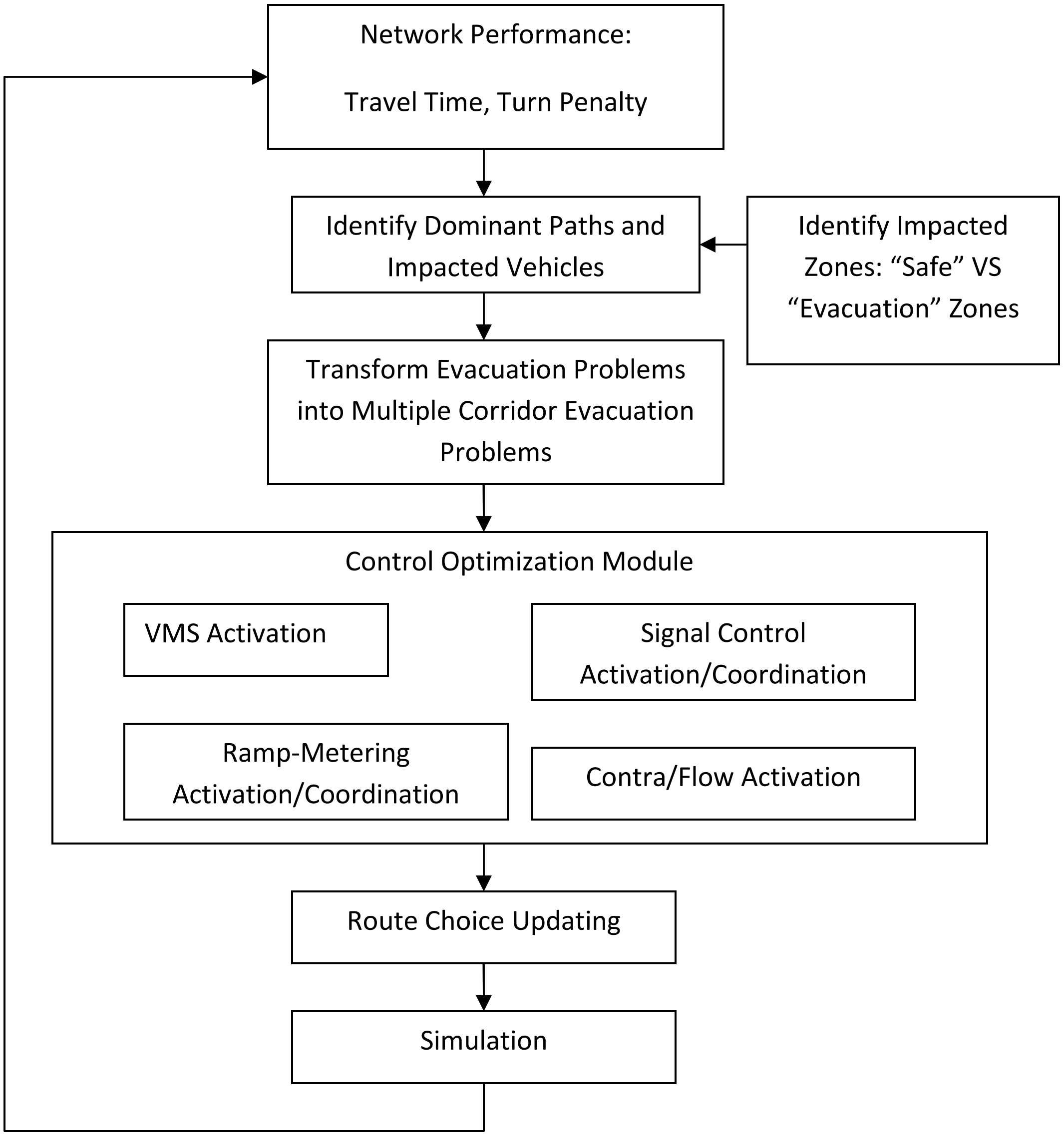


Figure 3.5: Reactive Integrated Control Strategy for Evacuation System (Hamdar et al., 2010)

On the other hand, at this stage of the study, three control strategies are illustrated for real-time scenarios:

Signalization: along arterials and minor roads, the signal design needs to provide priority to vehicles moving along the critical paths to avoid congestion. Accordingly, a maximum green time is allocated to the corresponding movements.

Variable Message Signs: the variable message plays a demand related role. These signs display messages on major roads so that traffic is diverted from the impacted areas to safer zones. The diversion can be done through providing alternative routes based on the entry point of the impacted zone.

Ramp Metering: using the already calibrated ALINEA factors, ramp metering is performed along the freeway critical links constituting a given critical paths

As for the Contra-flows, the freeway links constituting a critical path can be provided with extra capacity by allowing drivers along these paths to use all-but one lane from the opposite direction. The opposite direction lane volumes is already minimized through the use of variable message signs to control the demand. However, since this technique cannot be used appropriately in real-time compared to existing variable message signs, actuated signals and ramp meters, it will not be considered in the case-study illustrated in the next section.

With the above scheme, trip times and average stop times are generated for performance measures comparison. The next chapter illustrates the formulation in the used simulation software accompanied with a specific case-study along with some initial results.

CHAPTER 4 – COMPUTER SIMULATION AND MODELLING SET-UP

4.1. DYNASMART-P: A dynamic traffic simulation tool

“DYNASMART-P is a state-of-the art dynamic network analysis and evaluation tool designed to support the evaluation of proposed changes to local and regional transportation networks. Such changes could be informational or operational in nature”, Mahmassani et al., 2004. “DYNASMART-P has been used in our study for the simulation purpose due to its flexible properties. It can represent multiple user car classes in terms of operational performance, information availability, and user behavior rules. In addition, it can also model various control strategies such as ramp meters and traffic signals and can provide the ability to model the effects of the introduction of Advanced Traveler Information System (ATIS) and Advanced Traffic Management Systems (ATMS) on travel behavior and network performance.

As a result, DYNASMART-P models the evolution of the traffic flow in a traffic network. This model is also capable of representing the travel decisions to show a chain of activities at different locations in the network. Also, it is capable of employing different traffic management system concepts. Such concepts include; ramp metering, HOV/HOT Lanes, coordinated signal control, and localized VMS for speed advisories and diversion. In addition, congestion-related disturbances due to high volumes can be captured in this dynamic simulation module.

In DYNASMART-P driver behavior can be influenced by changing either the information that drivers are receiving or the network controls. In this simulation model, VMS responsive users get assigned their paths at the beginning of the simulation. They keep their path, unless they encounter the VMS. There are four types of VMS information, namely as follows.

(1) Speed Advisory

(2) Congestion Warning

(3) Optional Detours

(4) Mandatory Detours.

There are two main control devices which can be used to influence the driver's behavior, which are signal control and ramp metering. These devices are modified in terms of their operational logic to help in the impacts mitigation related to the disturbance during evacuation.

In the case of signal control adjustments in DYNASMART-P, the software too can allow the operator to determine the dominant paths in the network allowing, path-based signal coordination. DYNASMART-P CHART network have all its signalized intersections actuated. The main input parameters of interest are the maximum green time, the minimum green time, the amber time and the phasing time. It should be noted that it is helpful to mention at this stage that in the entire calibrated network:

- the maximum “maximum green time” is 159 seconds
- the minimum “maximum green time” is 13 seconds
- the maximum “minimum green time” is 50 seconds
- the minimum “minimum green time” is 5 seconds
- the maximum amber time is 5 seconds
- and the minimum amber time is 3 seconds”, Mahmassani et al., 2004

In the case of ramp metering, the operator has the ability to activate and deactivate the controllers and on the same time, has the ability to change the corresponding parameters. Regarding ramp metering, DYNASMART-P is constructed to allow the adjustment of the on-ramp flow rates based on the flow and downstream capacity on mainline freeway lanes. The logic implemented is similar to Papageorgiou’s ALINEA (Papageorgiou et al., 1998), which is a relatively simple feedback-control mechanism. This ramp meter model is formulated as follows:

$$q_t = q_{t-1} + \alpha(\beta - OCC) \quad \text{……………………………………..………………………...(iv)}$$

Where q_t = Ramp flow rate (vehicles/lane/hr) for the t^{th} period

$q_{t\text{-}1}$ = Ramp flow rate (vehicles/lane/hr) for the $(t\text{-}1)^{th}$ period

OCC = Measured downstream occupancy (percent time)

α = Occupancy-to-flow conversion rate (vehicles/lane/hr/percent time)

β = Maximum freeway downstream occupancy (percent time)., and

$$q_t = \begin{cases} Saturation\ flow\,rate\,(SFR) & if\ \ q_t \geq \ SFR \\ 288\ veh/hr/ln & if\ \ q_t < 288 \end{cases}$$ (Mahamassani et al., 2007)

The term *(β - OCC)* represents the excess downstream capacity (in terms of occupancy) available for entering vehicles. Therefore, the higher the β is, the more available capacity for entering vehicles. The term α may be regarded as a control factor, which controls the number of vehicles to enter the freeway via the on-ramp. Therefore, the higher α is, the more vehicles get to enter the freeway.

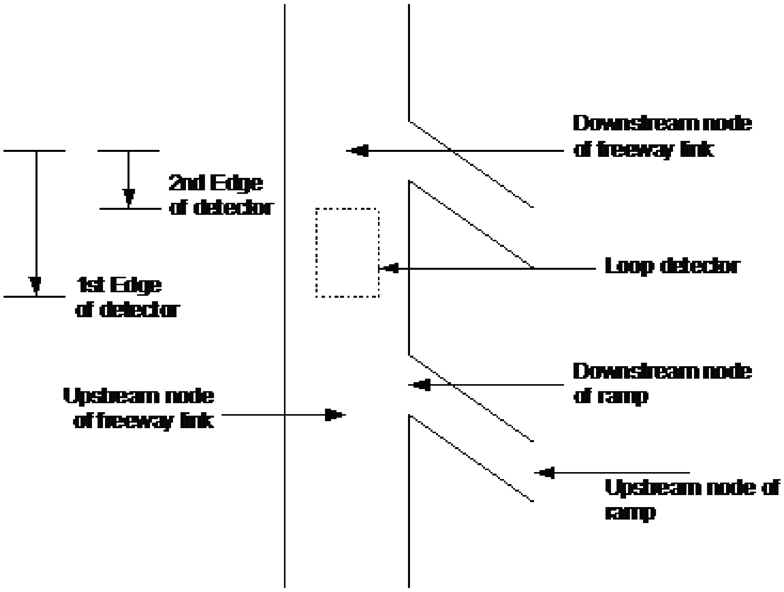


Figure 4.1: Important Location Information Regarding Ramp metering (Mahamassani et al., 2007)

The input parameters in DYNSMART-P for ramp metering are: number of metered ramps and their location, the rate by which they are updated, the time when they are active, the downstream link of the ramp, the location of the edges of the loop detector

(Figure 4.1) and the ramp metering ALINEA parameters. Calibrated for Paris urban network (Papageorgiou et al., 1998), the default ramp metering parameters are 0.320 for α and 0.20 for β. The ramp saturation rate is 0.5 veh/sec/ln or 1800 vphpl.

4.1.1. Dynamic Traffic Assignment

The case study is used to help demonstrating the value of control strategies when traffic congestion occur in the selected network due to an emergency in the Washington, DC (impacted area) and vehicles to be evacuated along the Baltimore, (MD) direction. As discussed, the case study uses a portion of the Maryland CHART network between Washington, DC and Baltimore, in conjunction with DYNASMART-P to conduct the analysis. The case study considers several scenarios (base-case versus evacuation case as discussed in the previous chapter) on the basis of an equal interval of time during the evacuation. For each scenario a series of integrated management corridor strategies were developed and analyzed.

The original network origin-destination (OD) demand levels were adopted in the analysis of the scenarios. The simulation planning horizon was set to be “t” minutes in order to insure that the entire “V” vehicles exit the impacted area network “t” minutes is the total time in minutes for the evacuation. All the vehicles are the passenger cars. User 5, or VMS responsive, was adopted in this analysis to allow the evaluation of different VMS strategies either alone or in tandem with the other measures.

The two scenarios will be run and after running the scenarios the total travel time for the impacted vehicles is calculated. This time starts when first impacted vehicle leaves the origin zone and ends when the last vehicle reaches destination.

4.1.2. Input VS. Output

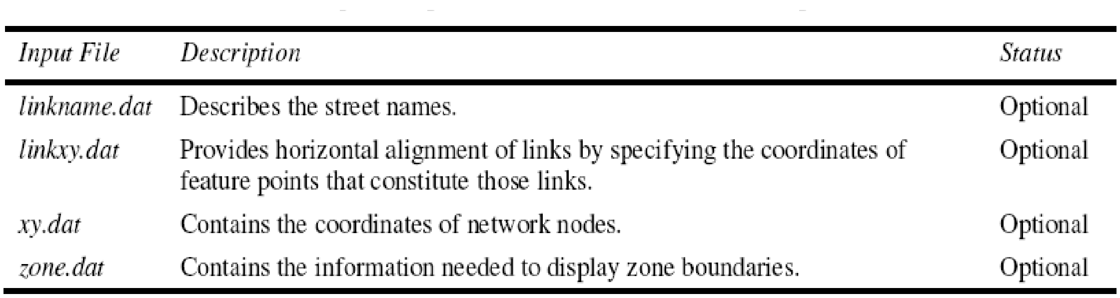
4.1.2.1. Input Files

DYNASMART-P requires two classes of input files: traffic simulation and graphical representation input files. Traffic simulation files must be present in the project working space; however, their contents may be empty (blank) depending on the scenario settings. Table 4.1 provides a brief description of what each simulation input file is used for.

Graphical representation files (Table 4.2) are optional. Without these files, the software would still function properly, but no graphical representation and no animation of the network and its associated traffic pattern would be available. Nevertheless it is strongly recommended that the user supplies these files to view animated traffic simulation results. To display the network within the graphical user interface (GUI), the user must at least specify the node coordinates (or more specifically, *xy.dat*). Note that in this document, the graphical representation input files and GUI input files are used interchangeably to illustrate the results.

Table 4.1 provides an overview of which input files are required for implementing various functionalities provided by DYNASMART-P.

Input File	*Description*	*Status*
ProjectName.dws	Contains information about the project name, DYNASMART-P version number, and location of the origin coordinates.	Required
bus.dat	Contains information regarding the buses, including the trajectories, location of stops, and dwell time.	May be empty
control.dat	Contains information regarding the type of traffic control at each node. If the control type is signal control, then phasing information for the signal is also included.	Required
demand.dat *demand_truck.dat* *demand_HOV.dat*	Contains information regarding the temporal and spatial distribution of demand for PCs, trucks, and HOVs.	Required
destination.dat	Specifies destination nodes.	Required
GradeLengthPCE.dat	Contains the PCE values for heavy vehicles based on link upgrade, length and heavy vehicle percentage.	Required
Incident.dat	Contains information regarding incidents in the network.	May be empty
leftcap.dat	Contains information regarding the left-turn capacity at signalized intersections (empirical numbers – can be obtained from the Highway Capacity Manual).	Required
movement.dat	Contains information regarding the allowed movements for vehicles (right-turns, left-turns, through, etc.).	Required
network.dat	Contains information regarding the network configuration, including zone and link characteristics.	Required
origin.dat	Specifies generation links.	Required
output_option.dat	Allows users to indicate whether or not certain output files should be created.	Required
path.dat	Contains the vehicle trajectory, in case it is needed to simulate a specific scenario where the vehicle paths are known. This file should be used in conjunction with vehicle.dat.	May be empty
pricing.dat	Contains information regarding the pricing of HOT/HOV Lanes.	May be empty
ramp.dat	Contains information regarding ramp metering scenarios including ramp locations, detector locations, ramp meter timings, etc.	May be empty
scenario.dat	Contains information regarding en-route information availability and basic simulation parameters.	Required
SuperZone.dat	Allows for aggregating several original TAZ's to a single zone.	May be empty
system.dat	Contains information regarding selection of the solution mode, the length of planning horizon, aggregation interval and assignment interval.	Required
TrafficFlowModel.dat	Contains the parameters of the traffic flow model types.	Required
vehicle.dat	Contains information regarding the individual vehicles (an alternative method to load vehicles).	May be empty
vms.dat	Contains information regarding the locations of VMS signs.	May be empty
WorkZone.dat	Contains the number of work zones to be simulated, their starting time, location, lane closure, reduced speed limits and the corresponding queue discharge rate.	May be empty
StopCap2Way.dat *StopCap4Way.dat*	Contains information regarding the capacity at stop-controlled intersections (2-way and 4-way).	Required
YieldCap.dat	Contains information regarding the capacity at yield-controlled intersections.	Required



Input File	*Description*	*Status*
linkname.dat	Describes the street names.	Optional
linkxy.dat	Provides horizontal alignment of links by specifying the coordinates of feature points that constitute those links.	Optional
xy.dat	Contains the coordinates of network nodes.	Optional
zone.dat	Contains the information needed to display zone boundaries.	Optional

Table 4.1: Traffic Simulation Input Files (Mahmassani et al., 2007)

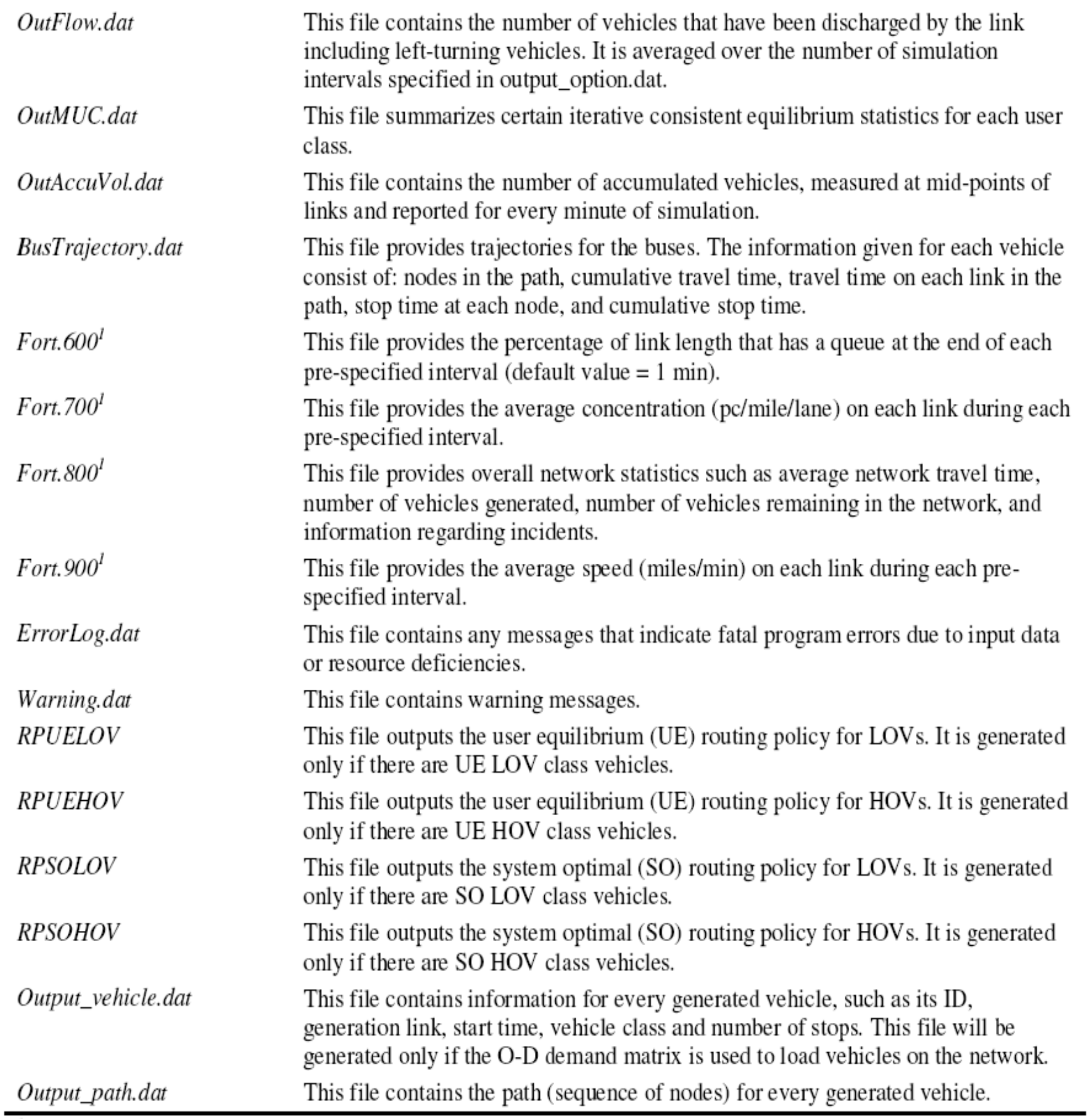
DYNASMART-P Function	*Related Input Files*
☐ Network Data	☐ *network.dat* ☐ *xy.dat* ☐ *Linkxy.dat* ☐ *LinkName.dat* ☐ *movement.dat* ☐ *TrafficFlowModel.dat*
☐ Intersection Control	☐ *control.dat* ☐ *leftcap.dat* ☐ *yieldcap.dat* ☐ *StopCap2Way.dat* ☐ *StopCap4Way.dat* ☐ *GradeLengthPCE.dat*
☐ Demand Generation	☐ *zone.dat* ☐ *origin.dat* ☐ *destination.dat* ☐ *SuperZone.dat* ☐ *demand.dat (for O/D matrix based combined demand)* ☐ *demand_truck.dat (for O/D matrix based truck demand)* ☐ *demand_HOV.dat (for O/D matrix based HOV demand)* ☐ *vehicle.dat (for trip chains and vehicle-based demand)* ☐ *path.dat (for trip chains and vehicle-based demand)*
☐ Bus Operation	☐ *bus.dat*
☐ Ramp Metering	☐ *ramp.dat*
☐ VMS signs	☐ *vms.dat*
☐ Accidents and lane closures	☐ *incident.dat* ☐ *workzone.dat*
☐ HOV/HOT lanes	☐ *pricing.dat*
☐ Solution Mode ☐ Planning Horizon ☐ Aggregation Intervals ☐ Assignment Intervals ☐ En-route Information ☐ Path Switching	☐ *system.dat* ☐ *scenario.dat*

Table 4.2: Graphical Representation and Animation (GUI) Input Data Files (Mahmassani et al., 2007)

4.1.2.2. Output Files

DYNASMART-P collects travel information for every vehicle in the network, which enables it to generate statistics (such as vehicle trajectories, system performance, and many more) at essentially any desired level of aggregation. Furthermore, network-wide averages are also readily available for several descriptors such as overall and basic trip times, entry queue times, stop times, and trip distances. Given the abundance and level of detail of output statistics in DYNASMARTP, the user may easily compute statistics for composite descriptors such as fraction of stopped time per trip time. The DYNASMART-P output files are briefly described in Table 4.3.

Output File	*Description*
SummaryStat.dat	This is the main output file for DYNASMART-P. It summarizes network performance for the given planning horizon. Overall vehicle statistics including trip times, travel times, stop times, entry queues, and travel distances are reported. It also includes vehicle loading and exiting information, statistics regarding HOT/HOV lanes, and a summary of the primary inputs.
VehTrajectory.dat	This file provides trajectories for individual simulated vehicles. Each trajectory is associated with a set of nodes (describing the path), the cumulative travel time, the travel time on each link in the path, the stop time at each node, and the cumulative stop time. This file is also used by the GUI to display animation of traffic simulation.
OutLinkGen.dat	This file contains the number of vehicles generated on each link during each simulation interval.
OutLinkVeh.dat	This file contains the number of vehicles (volume) on each link. It is averaged over the number of simulation intervals specified in output_option.dat.
OutLinkQue.dat	This file contains the number of vehicles in the queue on each link. It is averaged over the number of simulation intervals specified in output_option.dat.
OutLinkSpeedAll.dat	This file contains the average speed (mile/hr) on each link. It is averaged over the number of simulation intervals specified in output_option.dat.
OutLinkDent.dat	This file contains the average density (pc/mile-lane) on each link. It is averaged over the number of simulation intervals specified in output_option.dat.
OutLinkSpeedFree.dat	This file contains the average speed (mile/hr) for the moving vehicles on each link. It is averaged over the number of simulation intervals specified in output_option.dat. This file is similar to OutLinkSpeed.dat, but it excludes stopped vehicles.
OutLinkDentFree.dat	This file contains the average density (pc/mile-lane) for moving vehicles on the free-moving section of each link. It is averaged over the number of simulation intervals specified in output_option.dat.
OutLeftFlow.dat	This file contains the number of left-turning vehicles that are discharged from links. It is averaged over the number of simulation intervals specified in output_option.dat.
OutGreen.dat	This file contains the green time (seconds) for each approach. It is averaged over the number of simulation intervals specified in output_option.dat.



OutFlow.dat	This file contains the number of vehicles that have been discharged by the link including left-turning vehicles. It is averaged over the number of simulation intervals specified in output_option.dat.
OutMUC.dat	This file summarizes certain iterative consistent equilibrium statistics for each user class.
OutAccuVol.dat	This file contains the number of accumulated vehicles, measured at mid-points of links and reported for every minute of simulation.
BusTrajectory.dat	This file provides trajectories for the buses. The information given for each vehicle consist of: nodes in the path, cumulative travel time, travel time on each link in the path, stop time at each node, and cumulative stop time.
Fort.600[1]	This file provides the percentage of link length that has a queue at the end of each pre-specified interval (default value = 1 min).
Fort.700[1]	This file provides the average concentration (pc/mile/lane) on each link during each pre-specified interval.
Fort.800[1]	This file provides overall network statistics such as average network travel time, number of vehicles generated, number of vehicles remaining in the network, and information regarding incidents.
Fort.900[1]	This file provides the average speed (miles/min) on each link during each pre-specified interval.
ErrorLog.dat	This file contains any messages that indicate fatal program errors due to input data or resource deficiencies.
Warning.dat	This file contains warning messages.
RPUELOV	This file outputs the user equilibrium (UE) routing policy for LOVs. It is generated only if there are UE LOV class vehicles.
RPUEHOV	This file outputs the user equilibrium (UE) routing policy for HOVs. It is generated only if there are UE HOV class vehicles.
RPSOLOV	This file outputs the system optimal (SO) routing policy for LOVs. It is generated only if there are SO LOV class vehicles.
RPSOHOV	This file outputs the system optimal (SO) routing policy for HOVs. It is generated only if there are SO HOV class vehicles.
Output_vehicle.dat	This file contains information for every generated vehicle, such as its ID, generation link, start time, vehicle class and number of stops. This file will be generated only if the O-D demand matrix is used to load vehicles on the network.
Output_path.dat	This file contains the path (sequence of nodes) for every generated vehicle.

Table 4.3: Description of the Main Output Files of DYNASMART-P (Mahmassani et al., 2007)

4.2. Maryland CHART Test Network Description

This study aims at finding coordination between the control strategies along critical paths (corridors) to allow a faster and smoother evacuation. After identifying the components of the above control "optimization" logic, the formulated method is tested on a portion of the Maryland CHART network, USA. The portion considered consists of the I-95 corridor network between Washington, D.C. and Baltimore. The impacted area to be evacuated is the Washington DC and the safe area to be reached is the city of Baltimore. The network is bounded by I-695 in the north, I-495 in the south, US 29 to the west and I-295 to the east. The network includes four main freeways (I-95, I-295, I-495 and I-695), as well as two main arterials (US29 and Route 1). The Maryland CHART network reduces to 2182 nodes, 3387 links and 111 zones.

4.3. Model Calibration and Validation

Maryland DOT has provided a traffic analysis zone (TAZ) file, describing the zonal characteristics of the study area. The origin-destination file contains the static OD demand matrices for three time periods for the study area corresponding to the following modes: (1) SOV, (2) HOV2, (3) HOV3+, (4) Truck, and (5) Airport passengers. In addition, the three time periods are categorized as follows: (1) AM Peak, (2) PM Peak and (3) Off Peak.

The corridor network contains 111 OD demand zones, and the corresponding zonal scheme is extracted from the original TAZ boundary file in the original transportation planning data set that covers the Greater Washington DC area. Given the static planning OD Table for the entire area, the dynamic OD demand Table in the study network is obtained according to the following two steps. First, a static OD Table in the subarea is extracted from the complete OD Table by applying a DTA based network extraction and aggregation procedure. Second, archived link flow observations on 14 loop detectors along the corridor on 28th, October, 2004 are further used to calibrate and update the dynamic origin-destination demand Table, specifically for the traffic distribution structure and temporal structure of major OD pairs. The calibrated OD trip distribution pattern is shown in the following figure (Figure 4.2). Essentially, high volume of OD trip desires can be observed along I-95, 295, US Route 1 as well as the portion of the DC Beltway (495) in the study area.

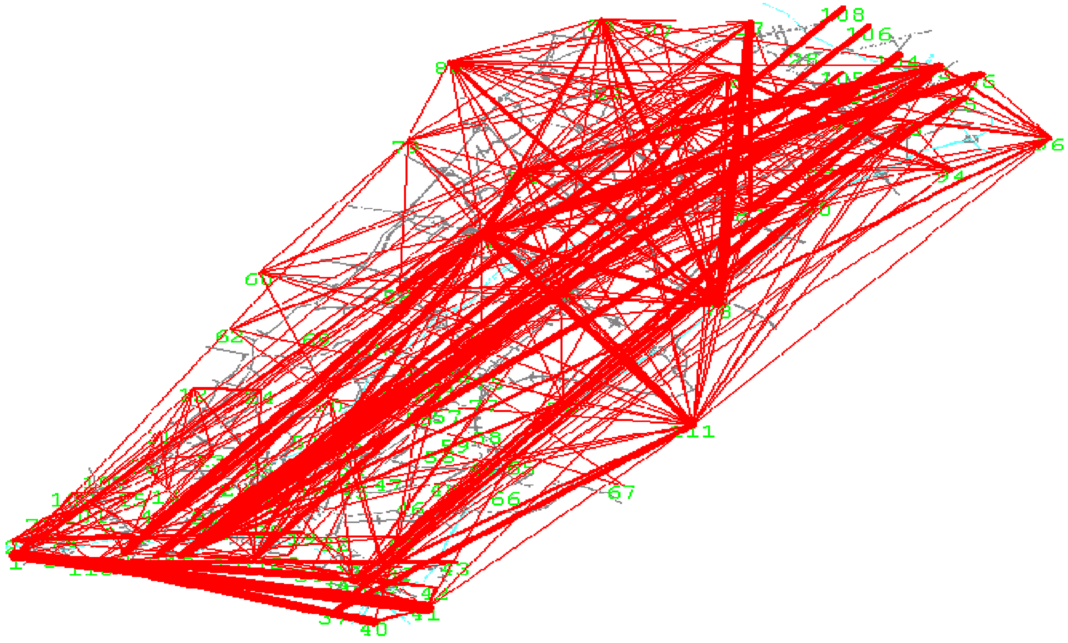


Figure 4.2: Origin-Destination Trip Distribution in Study Area after Off-line Calibration (Hamdar et al., 2005)

After the subarea network extraction and network modification, the final corridor network contains 2182 nodes and 3387 links. Based on signal locations and signal timing plans provided by the Maryland SHA, 351 signals are modeled in the study network, and actual signal phasing and timing data are converted to compatible DYNASMART-P format. Figure 4.3 plots the detailed signal locations in the network.

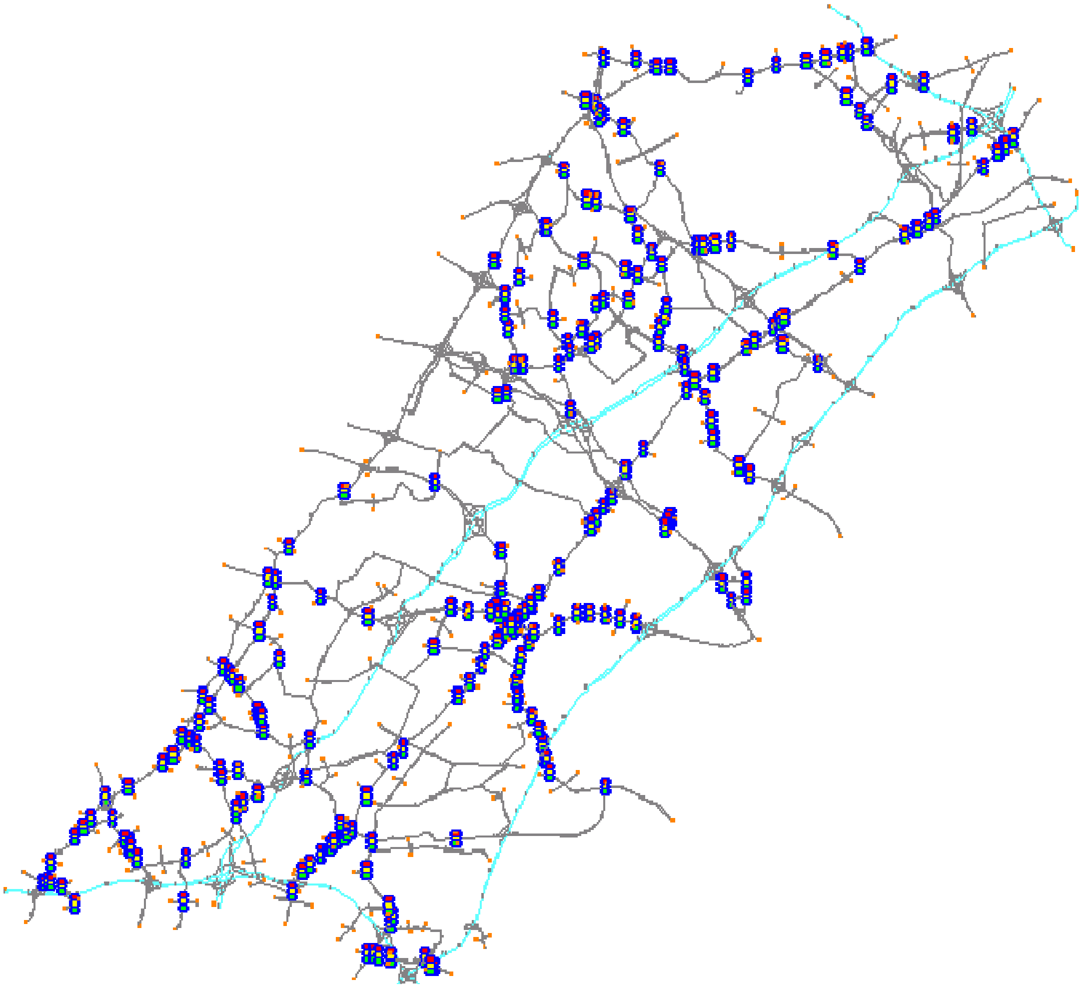


Figure 4.3: Signal Locations in the Corridor Network (Hamdar et al., 2005)

4.4. Concluding Remarks

In the model formulation and the DYNASMART-P software, the drivers have the choice of selecting the path for travel. As an example, it is quite obvious that some drivers will select path 1 and some will select path 2 during different scenarios. In the evacuation scenario, most of the vehicles will travel on path 2 (90% responsiveness); this is why path 2 will be with the installation of contra-flow and signal coordination operations in order to minimize the travel time and fast evacuation. This measure is an indirect indication of having low congestion on the original path 1, on which flow speed might be increased to save the time: by the end of all the scenarios on path 1, time is saved because of having less congested traffic on path 2; the travel time is saved by installing different control strategies. These two steps of our project have a combined effect on the whole evacuation time, which is reducing trip time from what should be expected in the case of no control coordination.

CHAPTER 5 - NUMERICAL ANALYSIS

5.1. An Evacuation Scenario: A Case Study

The network adopted in the case-study is the Maryland Chart Network. This network has 2182 nodes, 3387 links and 111 zones (Figure 1.1). The major routes are as follows:

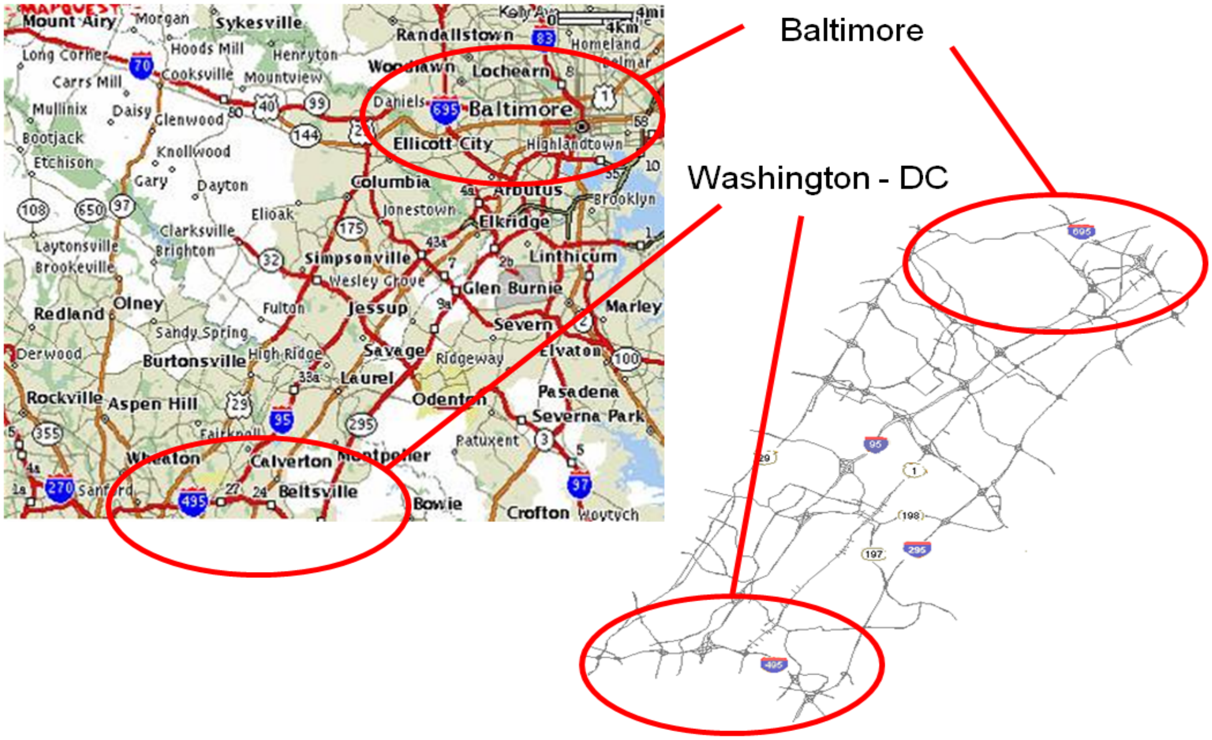
- Arterials: US-29 and Route 1
- Freeways: I95 N-S and -I295 N-S
- Beltways: I495 and I695 Beltways

The impacted zones constitutes the Northeastern part of Washington DC (Zones 10, 29, 30, 31, 33, 34, 35, 36, 37, 40 and 41 - within the DC beltway) and the safe zones are more rural “mid-zones” between Washington DC and Baltimore City so that traffic heading to Baltimore will not impede Baltimore outbound traffic and thus, causing additional congestion that can spill back along the Baltimore Washington Corridor and complicate the evacuation process.

A terrorist attack is assumed to be carried in the Washington DC Northeast area during lunch hours (12 PM to 2 PM) and the impact is assumed to be life threatening until 2 pm. The study period is a 6 hours period between 8 AM and 2 PM.

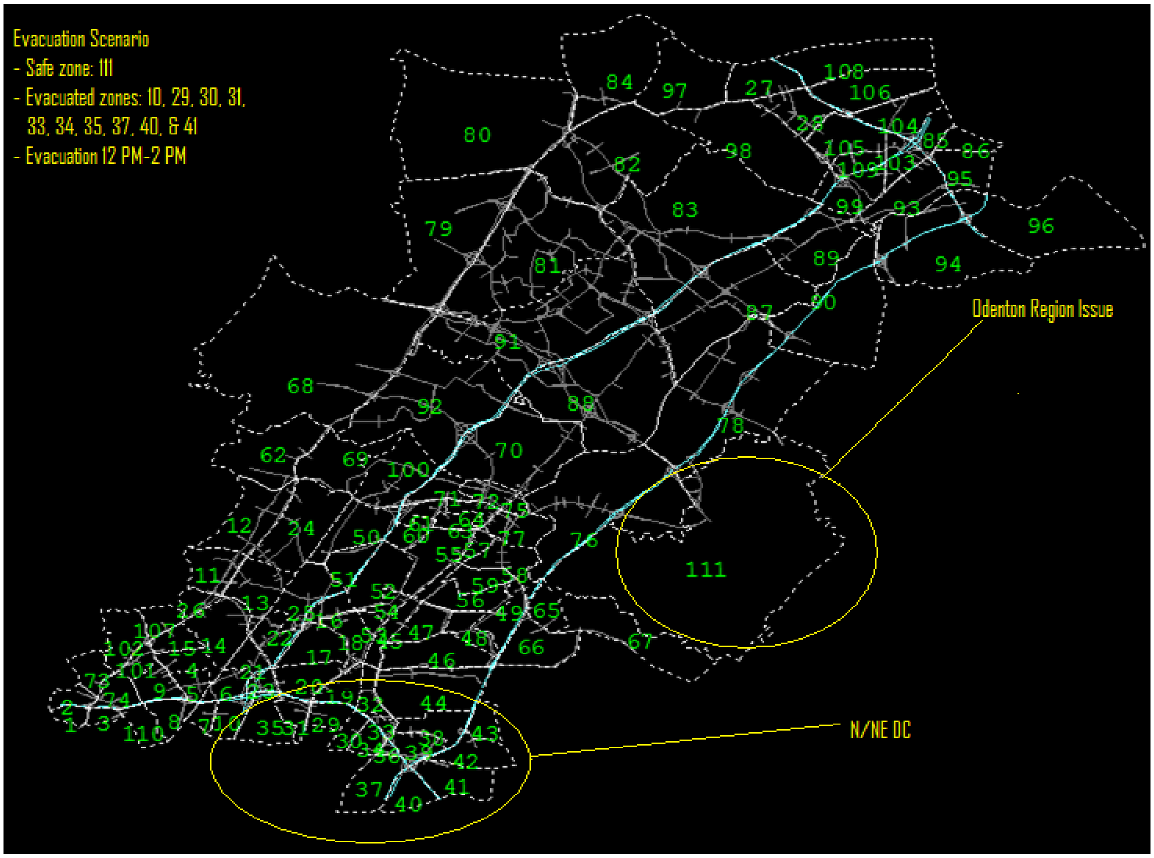
A number of scenarios are compared (24 in total); the first 6 scenarios correspond to evacuation without control coordination. Whereas, the remaining 18 scenarios corresponds to evacuation with the use of operational measures (control strategies). There are two major dominant paths in the network, one (Path 1) of which is along the freeway (Baltimore-Washington Parkway). The second dominant path (Path 2) runs mainly along route 1. Different scenarios are tested first by using Path 1 only and then by using paths 1 and 2. In all scenarios, the variable message signs “VMS” are activated first with 50% degree of responsiveness, which is followed by 75 % degree of responsiveness and finally by 100% degree of responsiveness. As for the remaining control strategies, ramp metering alone is activated first along the freeway (path 1) transferring vehicles from the impacted zones to the safe zone. Signal coordination (second control strategy) is activated after ramp metering along route 1 (Path 2). Finally, ramp metering and signal coordination are activated simultaneously. In this case, the different control strategies (Ramp metering + signalization) are coordinated and activated during the critical period (12PM to 2PM). Variable message signs “VMS” (with an optional detour towards the dominant paths) are installed at all the entrance and exits of the impacted area. First, the scenarios (without control coordination) are activated for Path 1 and Paths 1 & 2 for 50%, 75%, and 100% degree of VMS responsiveness. Results obtained from these simulation runs are then compared with the scenarios in which each control strategy is being used alone. Moreover, results obtained by using different control strategies are compared with each other and finally they are compared with the scenarios without control coordination.

Figure 5.1A shows the CHART Network to be integrated in Dynasmart-P software. A terrorist attack is assumed to be occurred in the Northeast region of Washington DC. This impacted area includes zones: 10, 29, 30, 31, 33, 34, 35, 36, 37, 40 and 41 respectively. The nearest safe area is assumed to be Baltimore, which includes one safe zone (111).



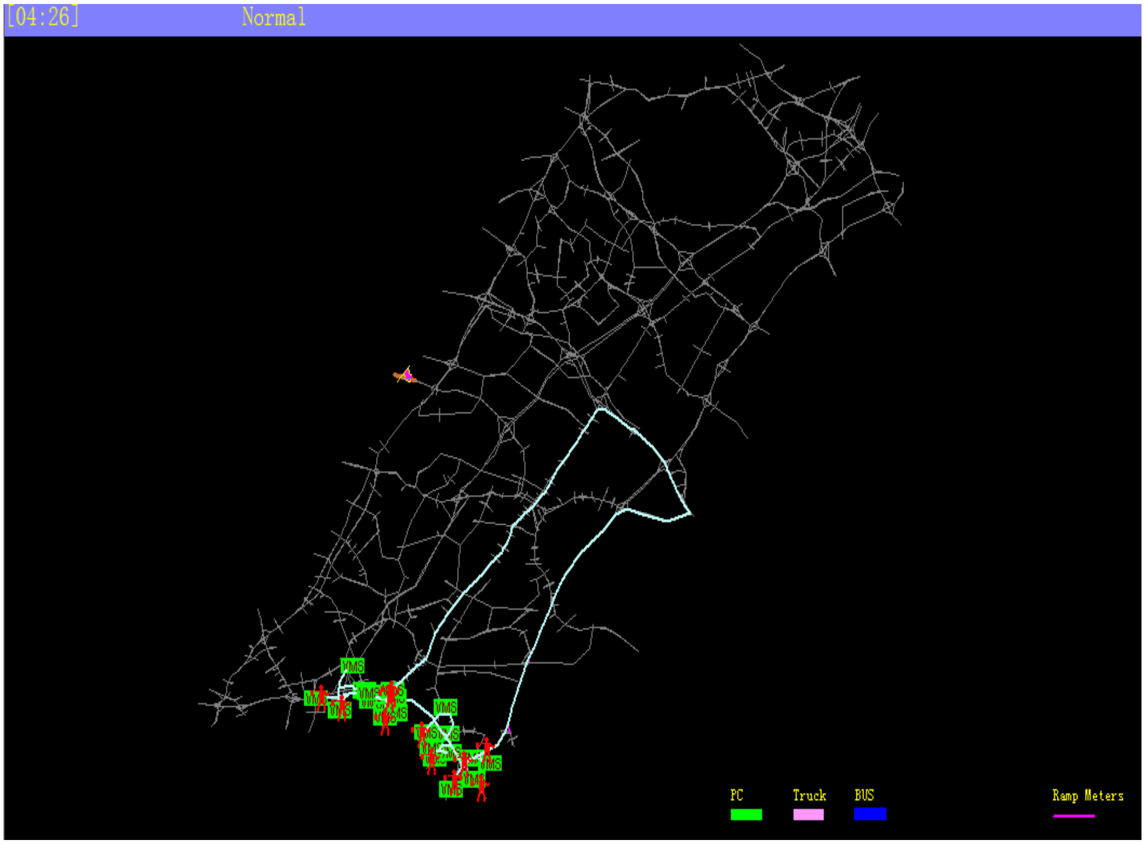
5.1 A. Chart Network Transformation to be integrated in Dynasmart-P Software

All the vehicles from the impacted area (impacted zones) need to be evacuated and transferred towards the safe zone, which is zone 111 (Figure 5.1B)



5.1 B: Zone Illustration in Case Study Figure

Critical paths are recorded to locate the coordination corridor along which the controls are activated dynamically (Figure 5.1 C).



5.1 C: A Dominant Paths Visualization

Figure 5.1: Mapping Maryland Chart Network in Case-Study

5.1.1. No Coordination (Path 1 and Path 1&2)

In this section, a total of 6 simulations are run without control coordination. In the first portion of this section, only one dominant path (Path 1) is used, in which all impacted vehicles are optionally detoured by the use of VMS installed at all the entrances and exits of the impacted area. First, three simulation runs are with three different degree of VMS responsiveness i.e. 50%, 75%, 100% (in each simulation run, one degree of responsiveness is used).

While mainly finding one dominant path, the diversion sub paths rely on a total of 18 VMS and 9 work zones recording the impacted vehicles and which are installed at all the exits of the impacted area (Figure 5.2).

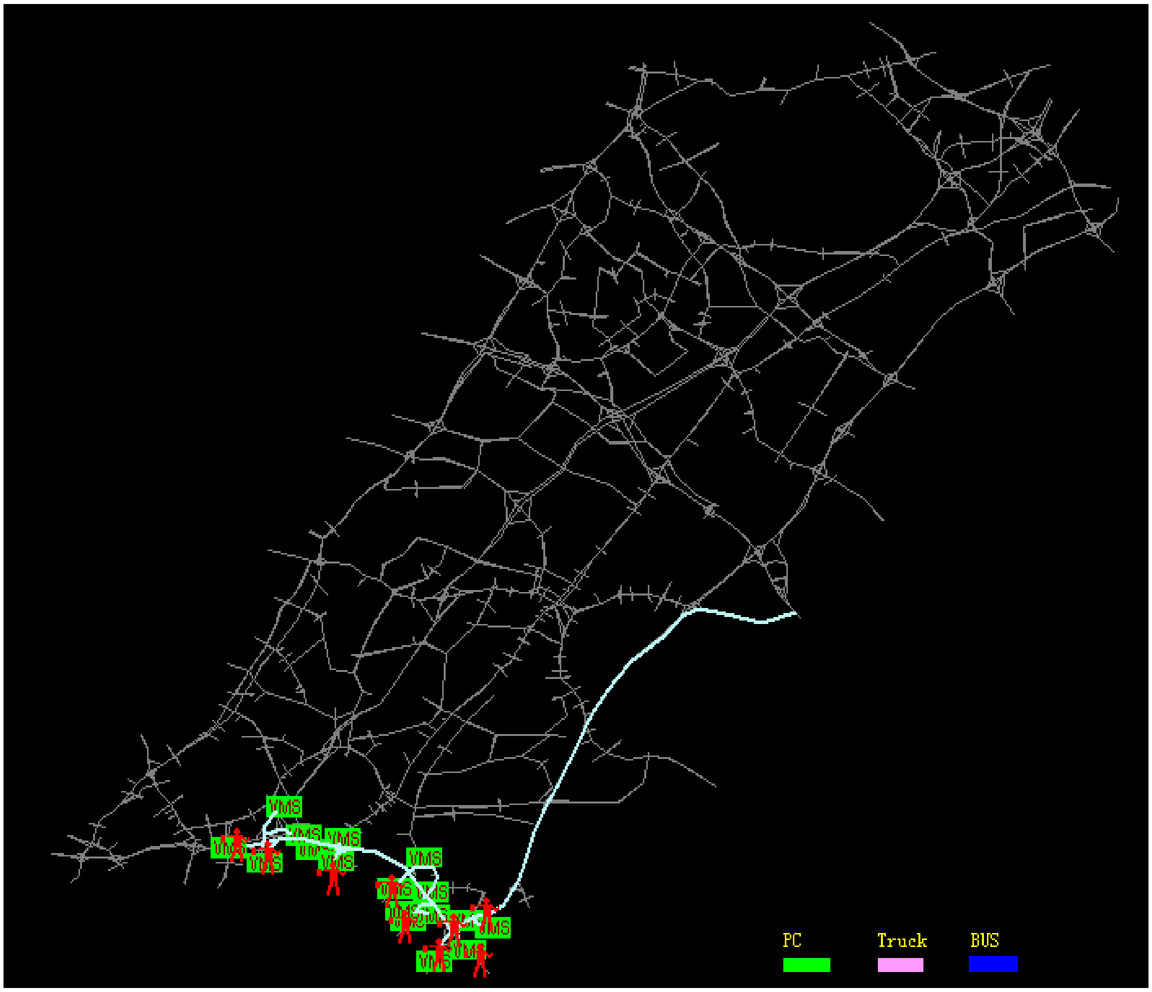


Figure 5.2: Dominant Path (Path 1) without Control Coordination

Following the same logic, the other three simulations are run mainly with the two dominant paths (K=2: Path 1 and Path1 & 2) with all the three degree of responsiveness.

While using two dominant paths, all the vehicles are given the optional detour by the VMS activated at all the entrances and exits of the impacted zones. Path 1 is along the Baltimore-Washington Parkway (Interstate 295), whereas Path 2 is along route 1 (US Route 1). In the 2-dominant Path case, total 23 VMS and 11 work zones are installed in order to tag the vehicles, as soon as they pass the work zones, which are installed at all the exits of the impacted area (Figure 5.3).

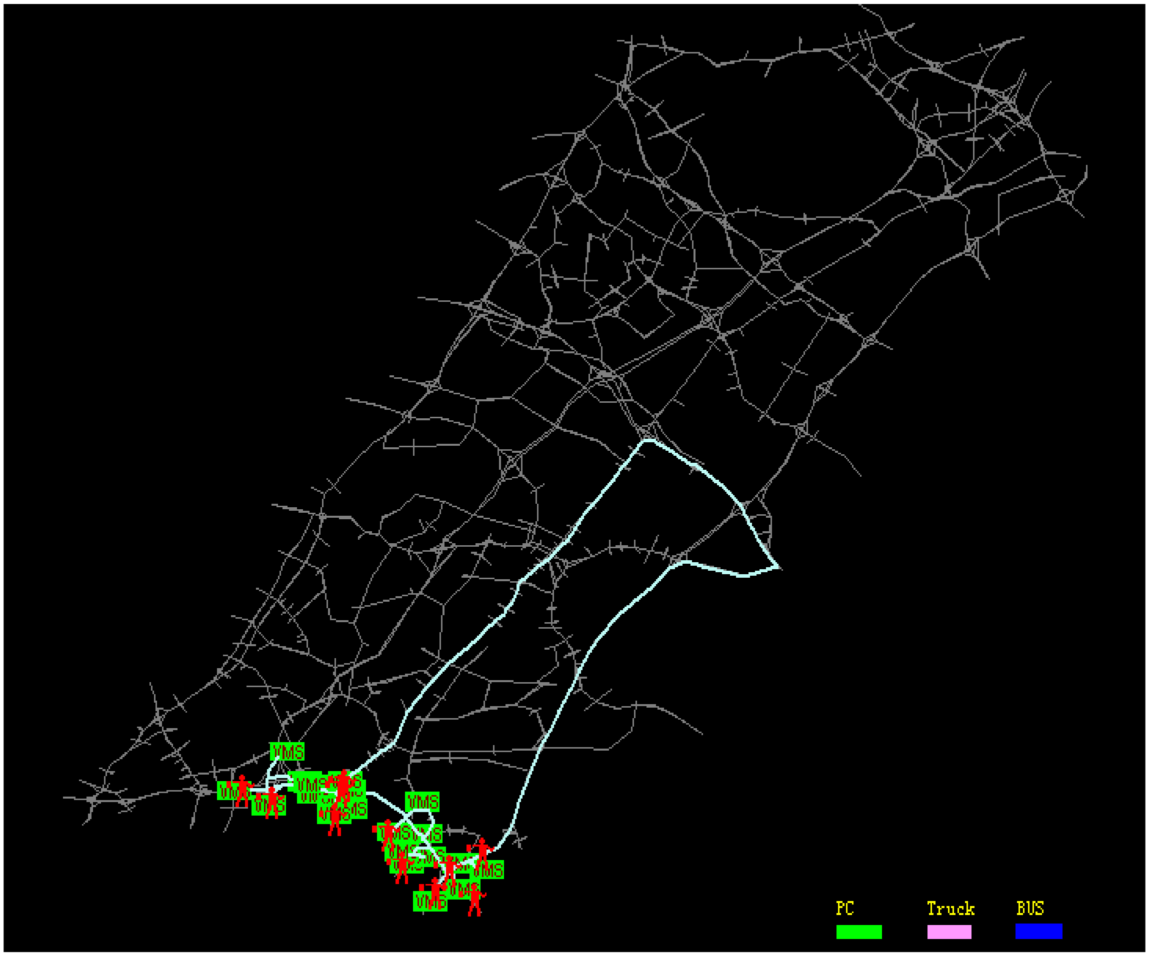


Figure 5.3: Dominant Paths (Path 1and Path1 & 2) without Control Coordination

5.1.2. Ramp Metering (Path 1 and Path 1&2)

In this section, a total of 6 simulation runs are adopted with the use of ramp metering only. Ramp meters are activated on all the ramps along Path 1 (freeway) to give priority to the vehicular flow on the freeway. In the first portion of this section only one dominant path (path 1) is used, in which all impacted vehicles are optionally detoured to Path 1 by the use of VMS installed at all the entrances and exits of the impacted area. First, three simulations are run only using path 1 (one dominant path) with three different degree of VMS responsiveness i.e. 50%, 75%, 100% (in each simulation, one degree of responsiveness is used).

Ramp meters (pink color) are installed along path 1 so that to give priority to the vehicular flow on this dominant path. A total number of 5 ramp meters are activated on all the ramps to the freeway for this purpose (Figure 5.4).

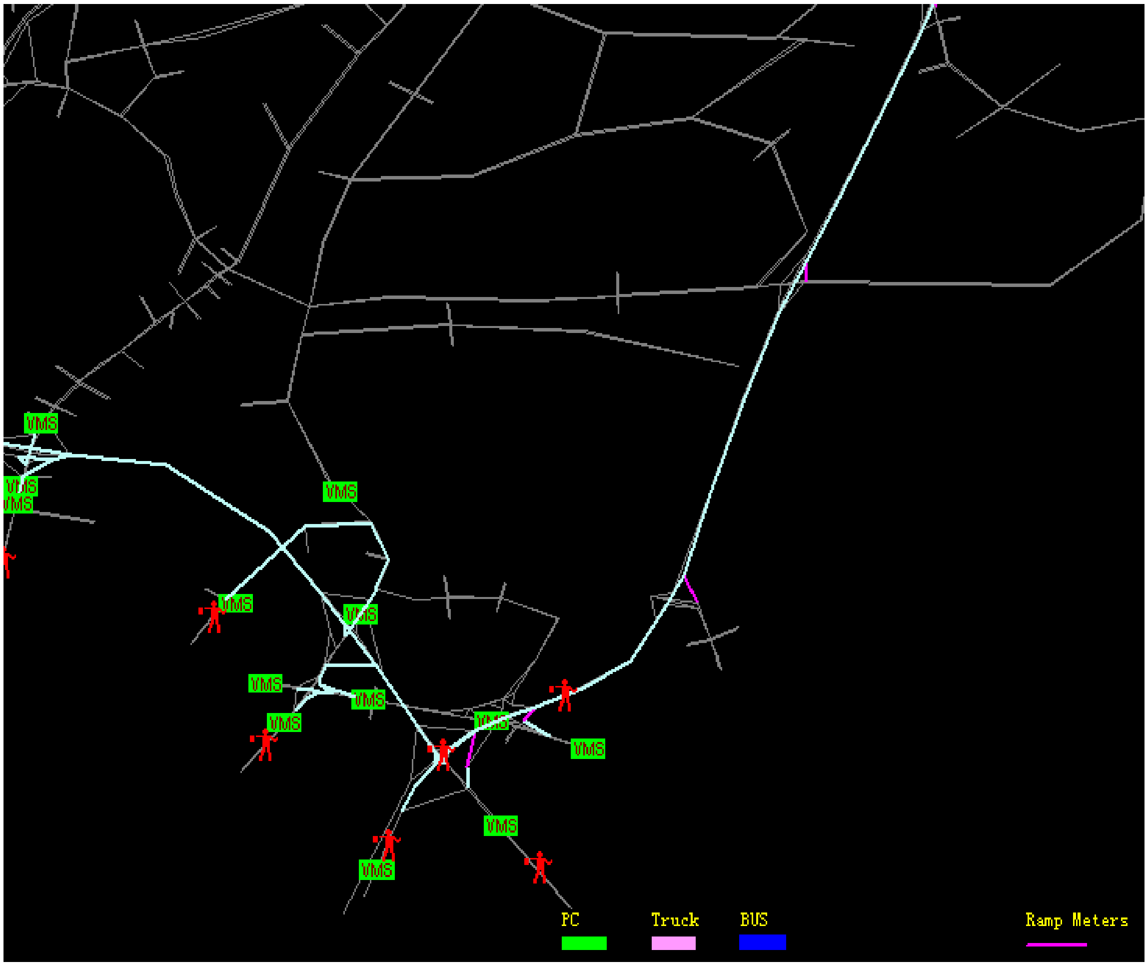


Figure 5.4: Dominant Path (Path 1) with Ramp Metering

Accordingly, the other three simulations are run by using the two dominant paths (path 1 and path1 & 2) with all the three degree of responsiveness. In this case, the same numbers of ramp meters are activated on the freeway. Two dominant paths been used, which are path 1 and path2 (Figure 5.5).

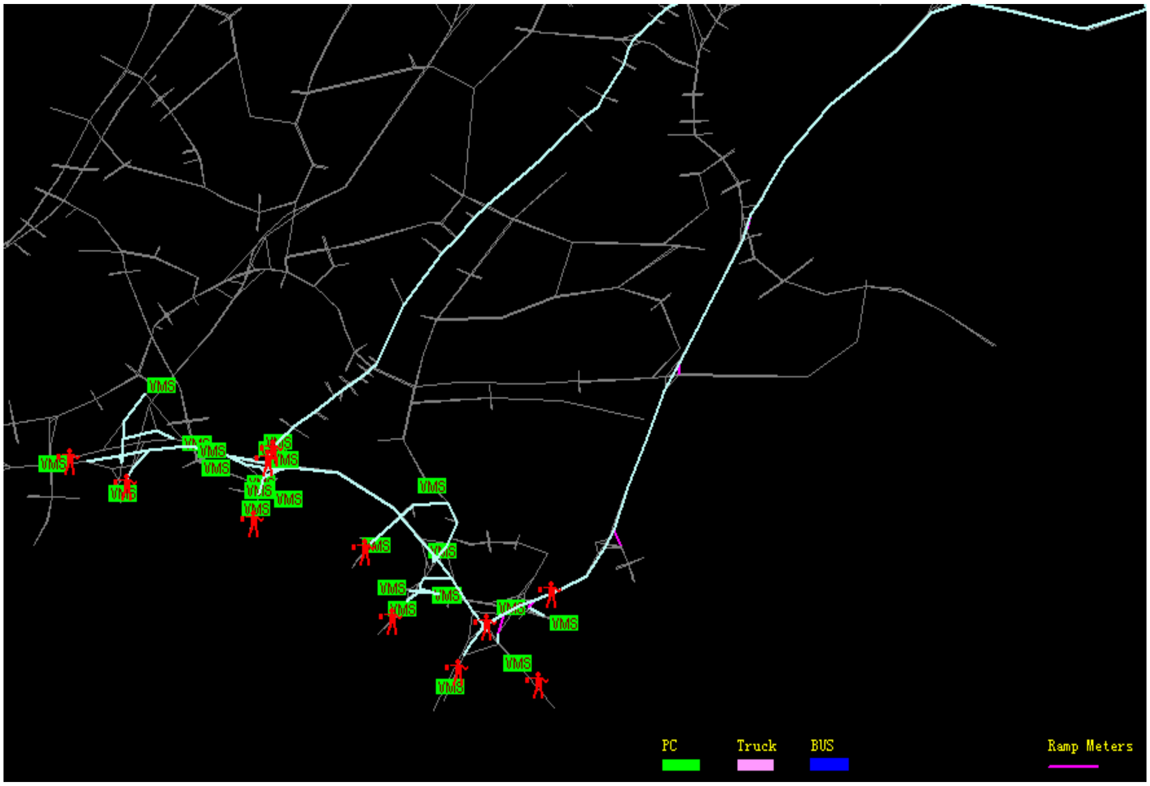


Figure 5.5: Dominant Paths (Path 1and Path1 & 2) with Ramp Metering

5.1.3. Signalization (Path 1 and Path 1&2)

In this section, a total 6 simulations are run with the use of signal coordination only. Signals along Path 2 (Route 1) are coordinated in a way that actuated control with provision of maximum max/min allowable greens (159 seconds, 59 seconds) along the dominant Path 2 is provided (Figure 5.6).

In the first portion of this section only one dominant path (Path 1) is used, in which all impacted vehicles are optionally detoured by the use of VMS installed at all the entrances and exits of the impacted area. Again, based on the number of impacted vehicles using different paths dynamically, three simulations are run first by using only Path 1 (one dominant path) with three different degree of VMS responsiveness i.e. 50%, 75%, 100% (in each simulation, one degree of responsiveness is used).

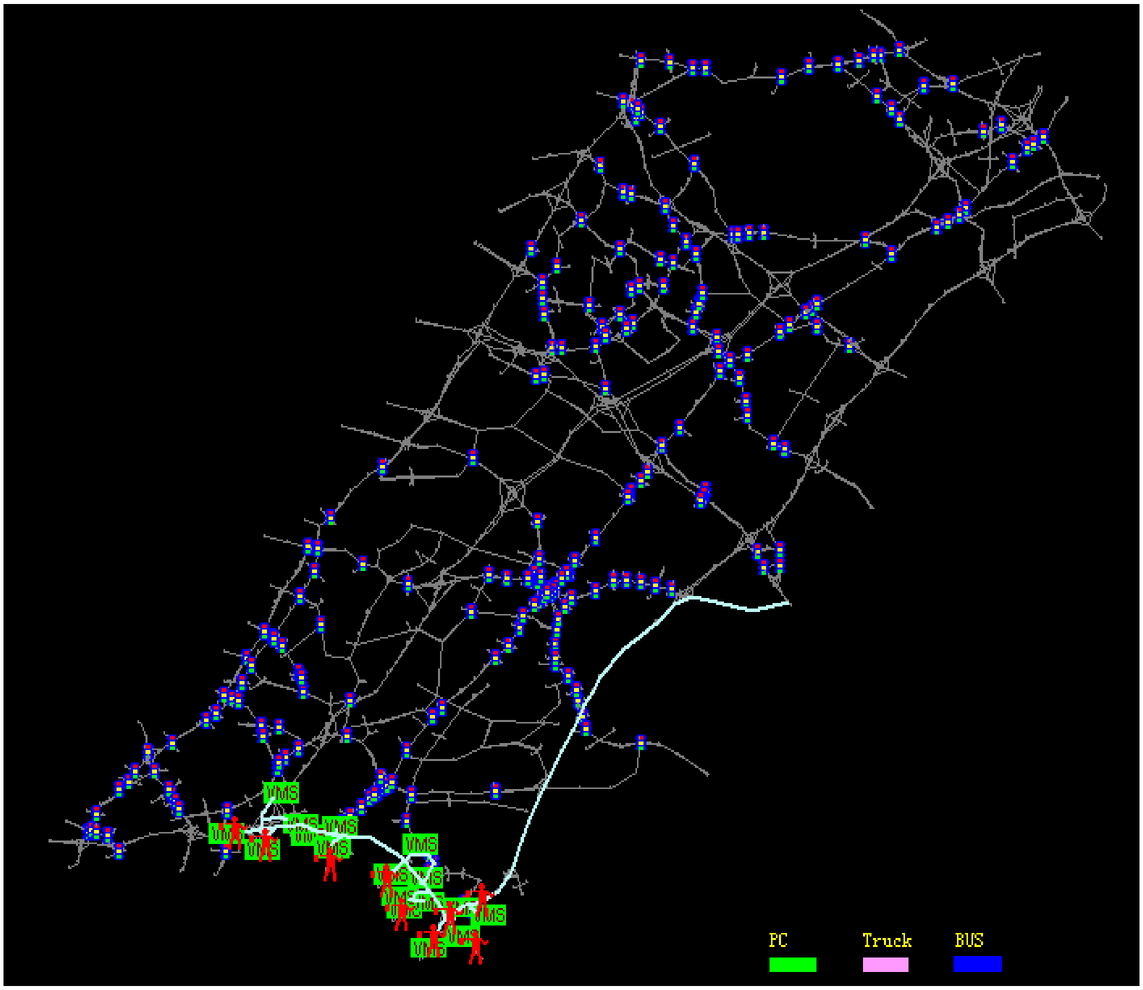


Figure 5.6: Dominant Paths (Path 1) with Signalization

Accordingly, the other three simulations are run by using the two dominant paths (k=2: Path 1 and Paths1 & 2) with all the three degree of responsiveness (Figure 5.7).

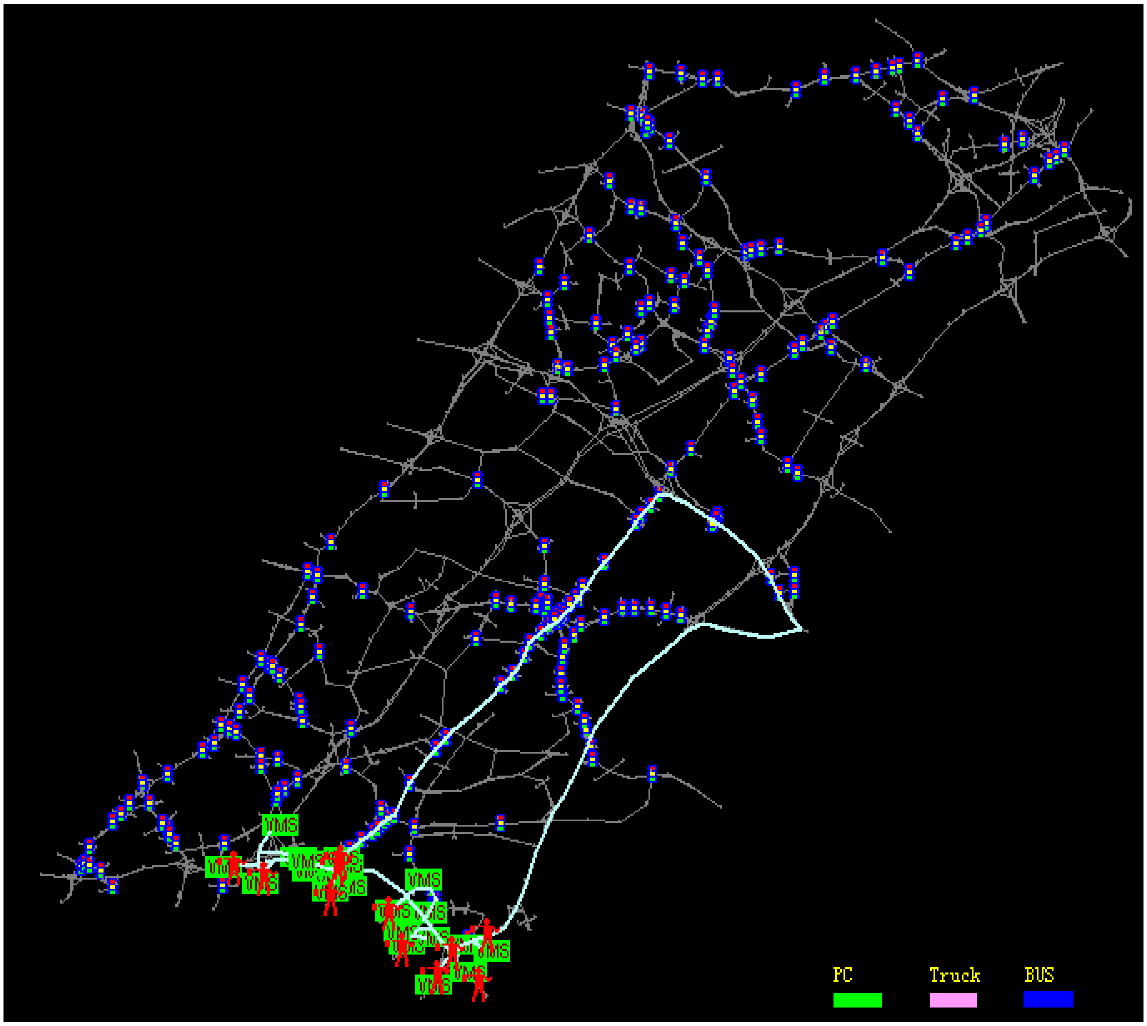


Figure 5.7: Dominant Paths (Path 1 and Path 1 & 2) with Signalization

5.1.4. Ramp Metering + Signalization (Path 1 and Path 1&2)

This section, a total 6 simulations are run with the use of two control strategies: Ramp metering and signal coordination. Ramp meters are activated on all the ramps along path 1 (freeway) in such a manner as to give priority to the vehicular flow on the freeway. Whereas, signals along Path 2 (Route 1) are coordinated in a way that actuated control with provision of maximum max/min allowable greens (159 seconds, 59 seconds) along the dominant Path 2 is provided.

In the first portion of this section only one dominant path (K=1: Path 1) is used, in which all impacted vehicles are optionally detoured by the use of VMS installed at all the entrances and exits of the impacted area. First, three simulation runs are adopted using only Path 1 (one dominant path based on the recorded number of impacted vehicles) with three different degree of VMS responsiveness i.e. 50%, 75%, 100% (in each simulation, one degree of responsiveness is used). In doing so, 9 work zones, 18 VMS, and 5 ramp meters along with the signal coordination (Path 2), are activated (Figure 5.8).

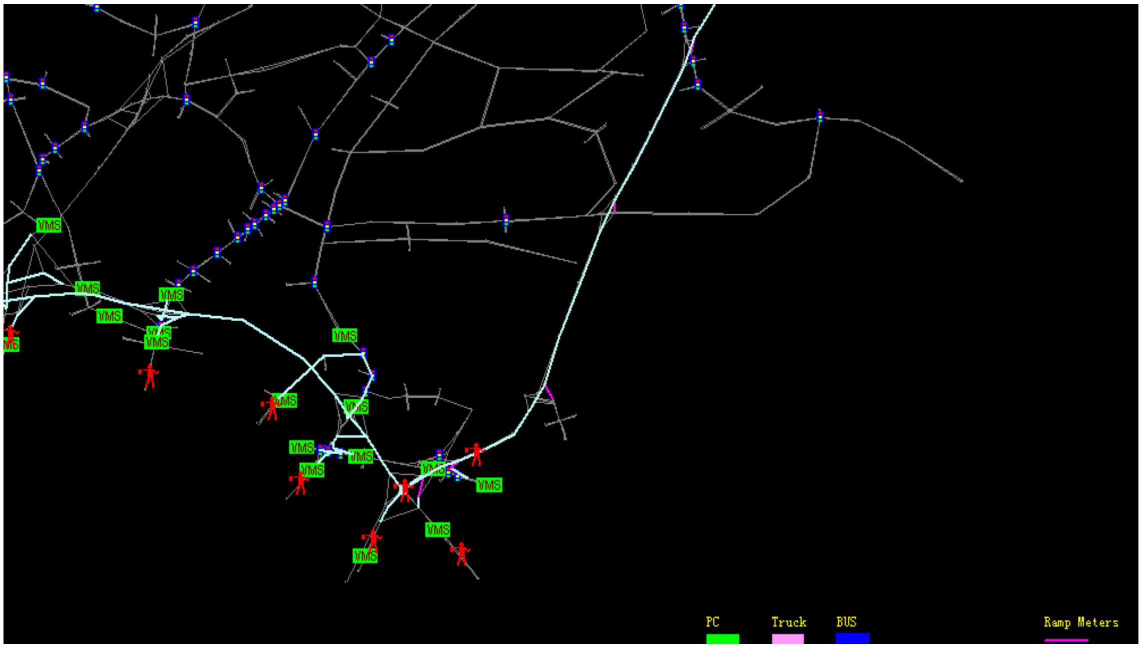


Figure 5.8: Dominant Paths (Path 1) with Ramp metering and Signalization

Accordingly, the other three simulations are run by using the two dominant paths (K=1: Path 1 and Paths 1 & 2) with all the three degree of responsiveness. In doing so, 11 work zones, 23 VMS, and 5 ramp meters along with the signal coordination (Path 2), are activated (Figure 5.9).

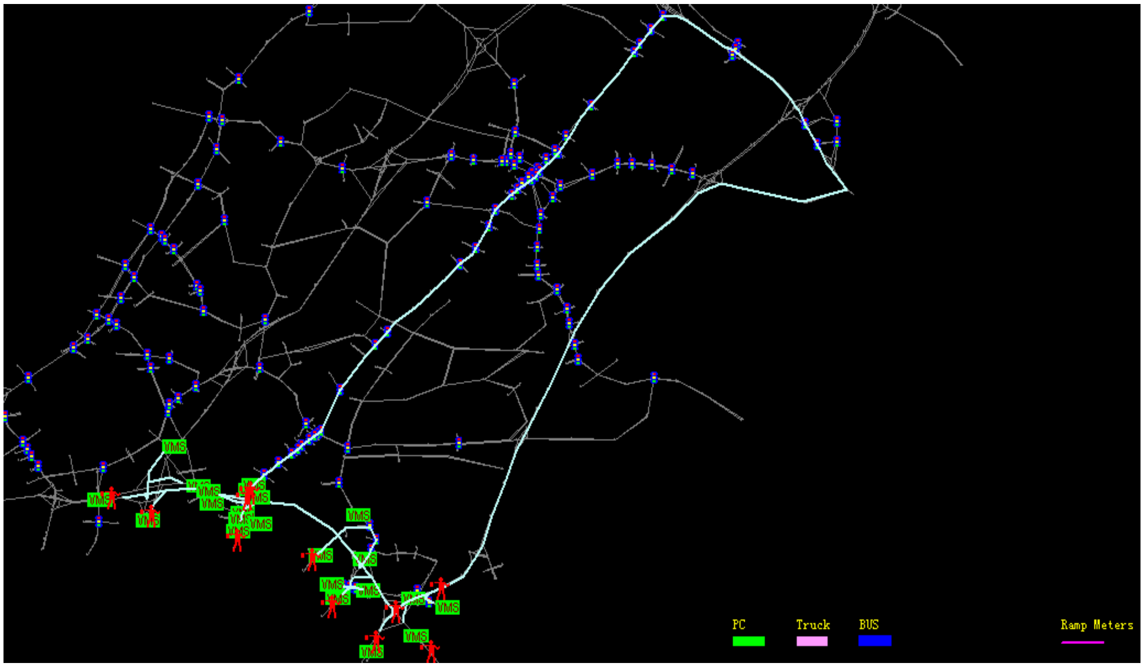


Figure 5.9: Dominant Paths (Path 1 and Path 1 & 2) with Ramp metering and Signalization

5.2. Analysis of Results

Transforming the Maryland Chart Network – mainly the corridor between Washington DC and Baltimore City (Figure 5.1 A), two measures of effectiveness (MOEs) are collected at this stage: 1) the average trip time is the average time needed for all vehicle to leave its origin to reach its destination based on the evacuation network loading scheme performed through the use of variable message signs; 2) the average stop time is the average time during a trip a vehicle is moving at an effective zero speed. The results are collected for all the scenarios, for both all the vehicles and the impacted vehicles (Table 5.1).

The results show clearly the improvement offered by the integrated control system adopting only the existing control technologies/instruments in the network. Using the variable message signs in and around the impacted zones, the number of impacted vehicles is reduced. This reduction is mainly related to the vehicles that were passing through the evacuation zones but with different origins and destinations and that are diverted via VMS.

5.2.1. Comparison of Results without Coordination with the Use of Ramp Meters

5.2.1.1. Number of Dominant Path Used = 1

As shown in Table 5.1, the average trip time without coordination with 50% VMS responsiveness is reduced from 16.59 minutes to15.93 minutes by using ramp meters only (as a control strategy) and the corresponding average stop time was changed from 1.35 minutes to 0.39 minutes. These two MOEs were reduced from 16.87 minutes to 15.39 minutes and from 1.39 minutes to 0.37 minutes for 75% VMS responsiveness. For 100% responsiveness, these values were reduced from 16.87 minutes to 15.16 minutes and from 1.39 minutes to 0.36 minutes. However, this improvement is not translated to a reduction in the MOE values for the entire network. The average trip time and stop time are either the same or just slightly decreased.

Moreover, such slight decrease re-indicates that this technique is not aimed to the overall minimization of trip time as it is the case for a general equilibrium traffic assignment problem. The changes adopted in this multi-level modeling system (changes in demand, one-shot simulation and dynamic critical paths identification) and the method by which the coordinated control strategy is integrated (dynamic corridor based coordination) prioritizes impacted vehicle even if this means an increase in the overall network level MOE values.

5.2.1.2. Number of Dominant Paths Used = 2

The average trip time without coordination with 50% VMS responsiveness is reduced from 14.31 minutes to13.28 minutes and the corresponding average stop time from 2.83 minutes to 1.85 minutes. These two MOEs were reduced from 14.40 minutes to 13.25 minutes and from 2.85 minutes to 1.8 minutes for 75% VMS responsiveness. For 100% responsiveness, these values were reduced from 14.27 minutes to 13.25 minutes and from 2.86 minutes to 1.8 minutes.

5.2.2. Comparison of Results without Coordination with the Use of Signal Coordination and Ramp Metering (Ramp metering + Signalization)

Results obtained from without control coordination scenarios compared the signalization and ramp metering + signalization scenarios, did not really give a high improvement as we had by activating ramp meters only along the freeway. This may be due to the fact that Dominant Path 2 (along which signals coordination is activated) is more time consuming path and has low traffic capacity with complex network geometry especially at the entrances and the exits of Route 1 with multiple signalization.

Table 5.1 shows detail comparison of the results of all the scenarios, followed by the graphical representation corresponding for each case.

Operational Measures Used	Aggregate Comparison	No. of Dominant Path used=1			No. of Dominant Paths used=2		
		(Degree of Responsiveness)			*(Degree of Responsiveness)*		
		50%	75%	100%	50%	75%	100%
	Average Trip Time (min)	13.92	13.88	13.88	13.89	13.87	13.87
	Average Stop Time (min)	1.05	1.02	1.02	1.06	1.03	1.03
No coordination	Impacted Sample (Veh)	3744	3504	3594	3920	3898	3898
	Average Trip Time (min)	16.59	16.87	16.87	14.31	14.4	14.27
	Average Stop Time (min)	1.35	1.39	1.39	2.83	2.85	2.86
	Average Trip Time (min)	13.82	13.79	13.8	13.86	13.85	13.85
	Average Stop Time (min)	1.02	1	1	1	1.05	1.05
Ramp Metering (R)	Impacted Sample (Veh)	3362	3448	3555	3899	3897	3897
	Average Trip Time (min)	15.93	15.39	15.16	13.28	13.25	13.25
	Average Stop Time (min)	0.39	0.37	0.36	1.75	1.8	1.8
	Average Trip Time (min)	14.01	13.96	13.98	13.98	13.93	13.93
	Average Stop Time (min)	1.06	1.04	1.05	1.05	1.04	1.04
Signals Coordination (S)	Impacted Sample (Veh)	3553	3593	3561	3922	3944	3946
	Average Trip Time (min)	15.89	15.32	15.84	13.22	13.59	13.54
	Average Stop Time (min)	0.39	0.36	0.38	1.78	1.89	1.89
	Average Trip Time (min)	14.06	14.07	14.07	13.99	13.98	14
	Average Stop Time (min)	1.14	1.15	1.16	1.11	1.09	1.09
R+S	Impacted Sample (Veh)	3643	3555	3556	3803	3715	3818
	Average Trip Time (min)	15.22	15.6	16.17	13.52	13.73	13.66
	Average Stop Time (min)	0.36	0.38	0.39	1.85	1.94	2

Table 5.1: Exploratory Results – Maryland Chart Network Case Study

The percentage differences between the results obtained from the simulation runs without any coordination and with the use of control strategies, have also been analyzed. First, the results obtained by activating ramp meters are compared with the results obtained from without any coordination. By activating ramp meters, there was an overall decrease in the average trip time and average stop time. Average trip time and average stop time for all the vehicles in the network were decreased by 1% and 3%, when 50% vehicles responsiveness and one dominant path was used. In this case, the maximum decrease was observed for 50% vehicles responsiveness when two dominant paths were used. The average trip time was decreased by 1% and average stop time was decreased by 6% (Table 5.2).

The maximum decrease in the number of impacted vehicles was 11% for 50% vehicles responsiveness to the variable message signs, while using one dominant path. Accordingly, maximum percentage decreases were observed for 75% and 100% VMS vehicles' responsiveness (by use of ramp meters only), where average trip time and average stop time, for impacted vehicles, were decreased by 9% & 74%, and 11% & 75%, while using one dominant path i.e., Path 1 (Table 5.2).

In the signal coordination cases, as it was observed for ramp metering, the maximum decrease in percentage of the impacted vehicles was observed for 50%, 75%, and 100% VMS responsiveness, while using one dominant path (path 1) was 6% (Table 5.2).

When ramp meters and signal coordination were coordinated at the same time, the percentage decrease in the average trip time and average stop time for the impacted vehicles, for all three VMS responsiveness (50%, 75%, and 100%) were 9% & 74%, 8% & 74%, and 5% & 73%, while using one dominant path (Table 5.2). This family of scenarios provides us with the most promising results in terms of average trip time and average stop time for the impacted vehicles. Among them, the highest decrease is when; one dominant path is used with 50% VMS responsiveness. This also shows that when two control strategies (Ramp metering + Signal coordination) are coordinated together, it will give the lowest average trip time and average stop time for the impacted vehicles. Accordingly in conclusion, this scenario actually helps the vehicles to transfer from the impacted area to the safe area in a lesser possible time.

No Operational Measures Used	Aggregate Comparison	No. of Dominant Path used=1			No. of Dominant Paths used=2		
		(Degree of Responsiveness)			*(Degree of Responsiveness)*		
		50%	75%	100%	50%	75%	100%
	Average Trip Time (min)	13.92	13.88	13.88	13.89	13.87	13.87
	Average Stop Time (min)	1.05	1.02	1.02	1.06	1.03	1.03
No coordination	Impacted Sample (Veh)	3744	3504	3594	3920	3898	3898
	Average Trip Time (min)	16.59	16.87	16.87	14.31	14.4	14.27
	Average Stop Time (min)	1.35	1.39	1.39	2.83	2.85	2.86

Percentage difference (+% or -%) by comparing results obtained by using operational measures with the results obtained by without coordination

Operational Measures Used	Aggregate Comparison (+% or -%)	No. of Dominant Path used=1			No. of Dominant Paths used=2		
		(Degree of Responsiveness)			*(Degree of Responsiveness)*		
		50%	75%	100%	50%	75%	100%
	Average Trip Time	-1%	-1%	-1%	-1%	-1%	-1%
	Average Stop Time	-3%	-2%	-2%	-6%	2%	2%
Ramp Metering (R)	Impacted Sample	-11%	-2%	-1%	-1%	-1%	-1%
	Average Trip Time	-4%	-9%	-11%	-8%	-8%	-8%
	Average Stop Time	-72%	-74%	-75%	-39%	-37%	-38%
	Average Trip Time (min)	1%	1%	1%	1%	1%	1%
	Average Stop Time (min)	1%	2%	3%	-1%	1%	1%
Signals Coordination (S)	Impacted Sample (Veh)	-6%	3%	-1%	1%	2%	2%
	Average Trip Time (min)	-5%	-10%	-7%	-8%	-6%	-6%
	Average Stop Time (min)	-72%	-74%	-73%	-37%	-34%	-34%
	Average Trip Time (min)	1%	1%	1%	1%	1%	1%
	Average Stop Time (min)	8%	11%	8%	4%	5%	5%
R + S	Impacted Sample (Veh)	-3%	2%	-2%	-3%	-5%	-2%
	Average Trip Time (min)	-9%	-8%	-5%	-61%	-6%	-6%
	Average Stop Time (min)	-74%	-74%	-73%	-35%	-32%	-31%

Table 5.2: Exploratory Results – Percentage differences

5.2.2.1. Graphs

Earlier, we explained the results in form of percentage decrease: at this stage, the following graphs show, average trip time and average stop time for all the impacted vehicles in all the scenarios run for 50% VMS responsiveness, in terms of time (minutes). The lowest average trip time (13.25 minutes) is obtained when only ramp meters and two dominant paths are used (Figure 5.10).

In terms of average stop time, it was lowest (0.36 minutes) when ramp metering and signalization are coordinated together and one dominant path was used (Figure 5.10).

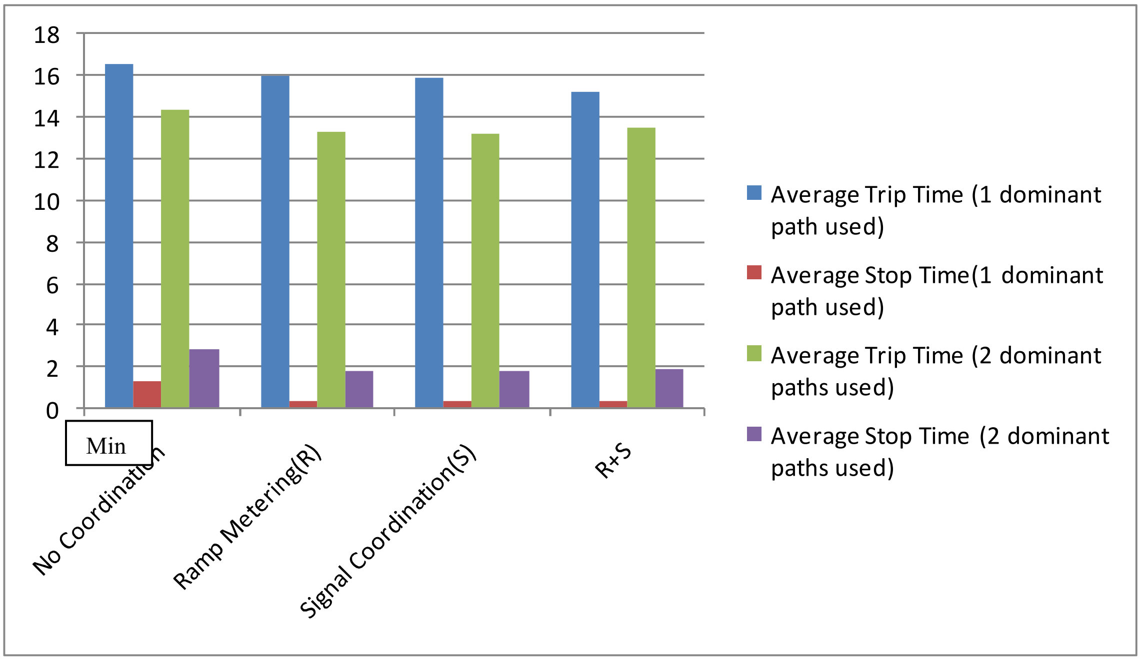


Figure 5.10: Average Trip Time and Stop Time for different Scenarios (50% VMS Responsiveness)

In the scenarios corresponding to 75% VMS responsiveness, the lowest average trip time for the impacted vehicles is 13.25 minutes, when only ramp meters are used with two dominant paths. However, for the average stop time of the impacted vehicles, it is 0.37 minutes when ramp meters are activated with one dominant path (Figure 5.11).

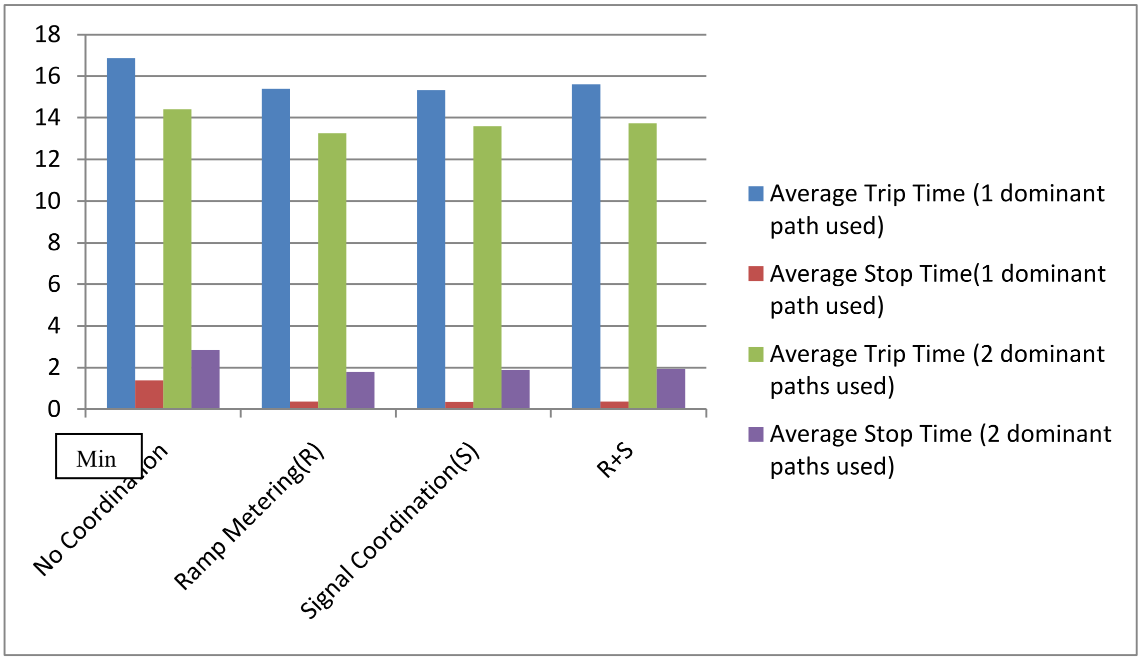


Figure 5.11: Average Trip Time and Stop Time for different Scenarios (75% VMS Responsiveness)

For 100% VMS responsiveness, the lowest average trip time and average stop time of the impacted vehicles are, when ramp meters are activated alone with one dominant path, 13.35 and 0.36 minutes respectively (Figure 5.12).

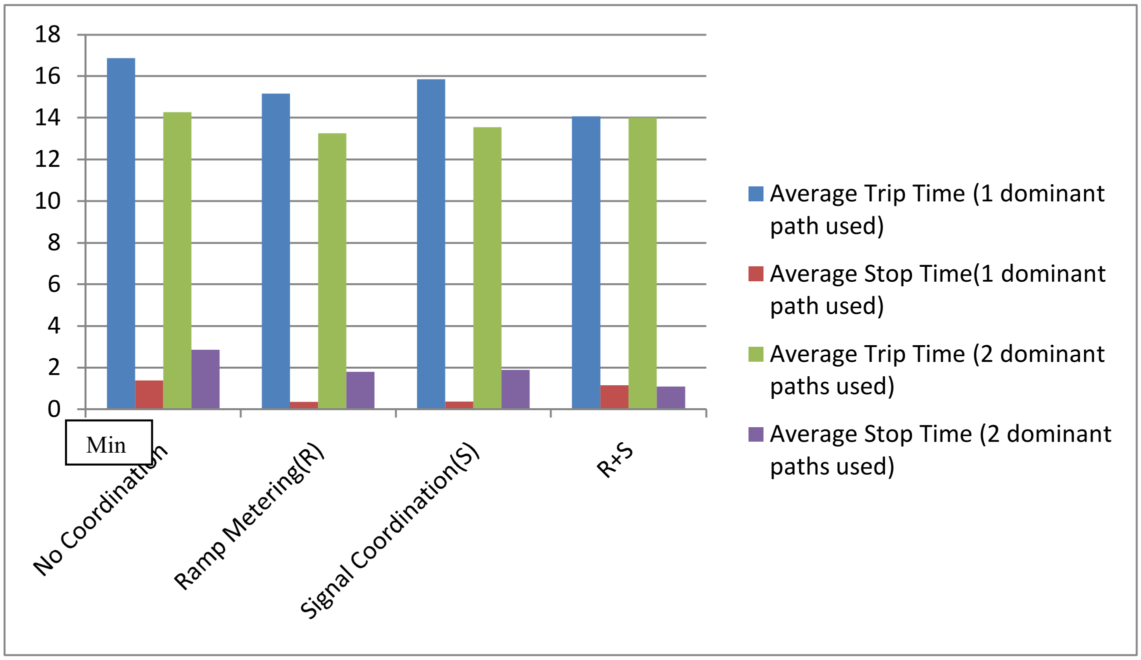
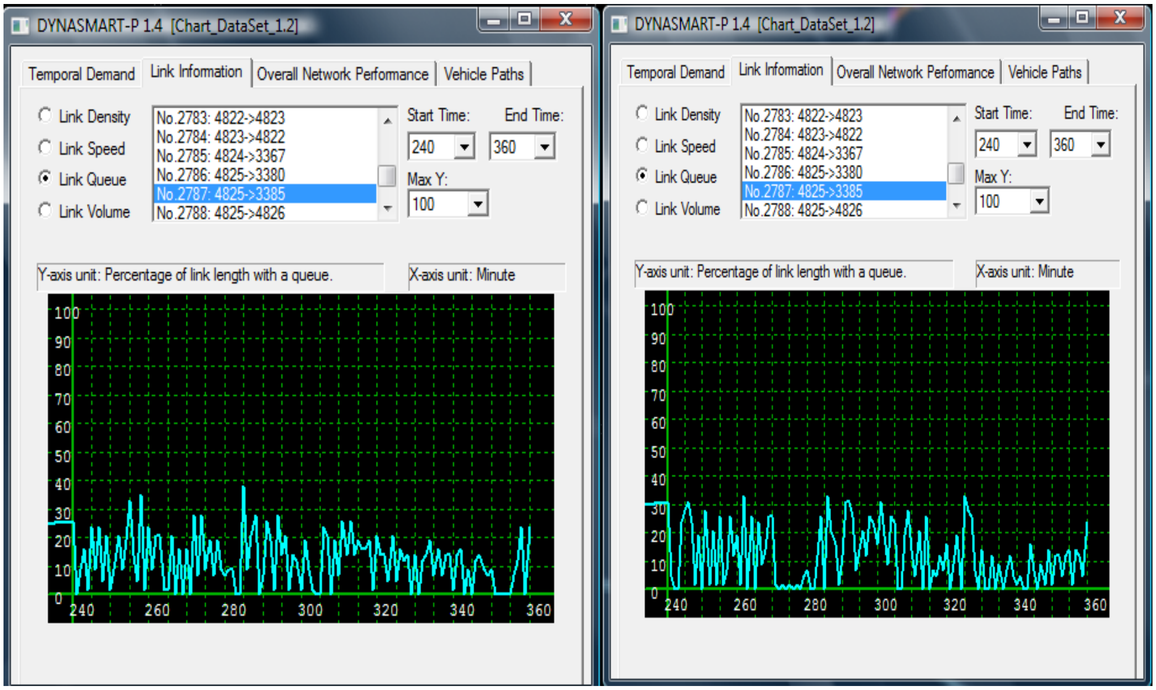


Figure 5.12: Average Trip Time and Stop Time for Different Scenarios (100% VMS Responsiveness)

Figure 5.13 has been taken from the simulations, in which two scenarios have been compared for the percentage of link length with a queue. First graph (Figure 5.13A) has been taken from the simulation with the use of control strategies, i.e., Ramp Metering and Signal Coordination (Signalization). While, the other graph (5.13B) is from the no coordination scenrio run.

In the first graph, the average percentage of the link length with a queue is approximately 26% and its highest value accurs at time 280 minutes, whereas the second graph shows a percentage queue length exceeding 30%.



DYNASMART-P 1.4 [Chart_DataSet_1.2]

○ Link Density
○ Link Speed
● Link Queue
○ Link Volume

No.2783: 4822->4823
No.2784: 4823->4822
No.2785: 4824->3367
No.2786: 4825->3380
No.2787: 4825->3385
No.2788: 4825->4826

Start Time: 240
End Time: 360
Max Y: 100

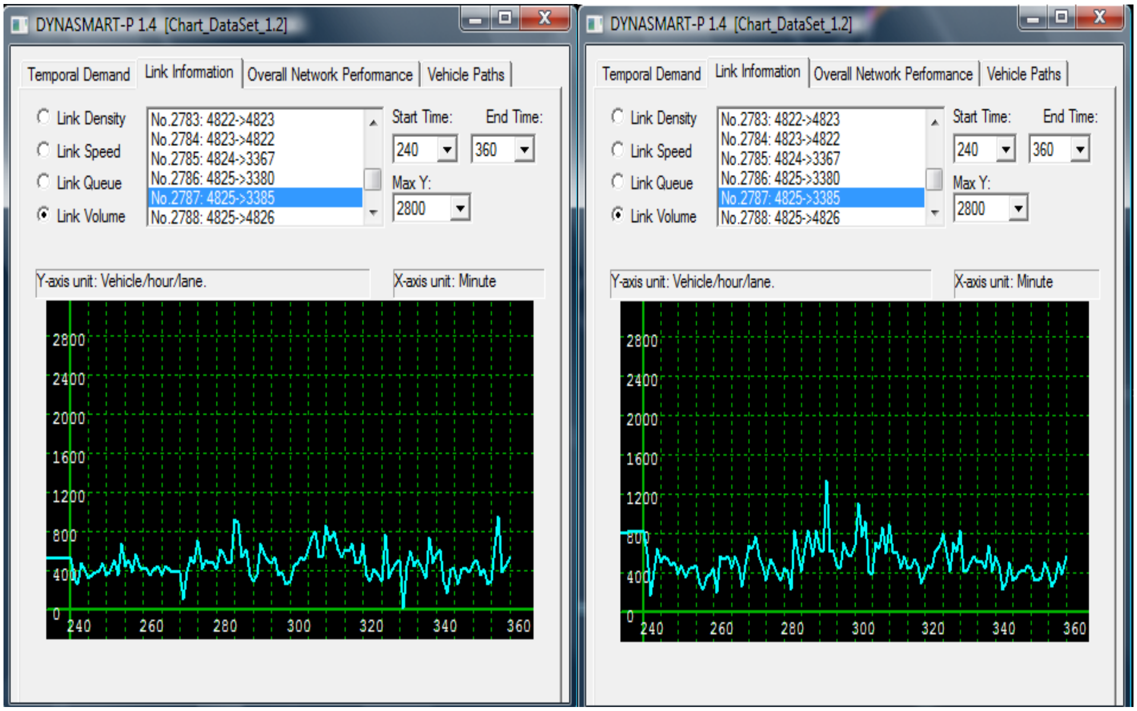
Y-axis unit: Percentage of link length with a queue.
X-axis unit: Minute

Figure 5.13A: R+S with one dominant path

Figure 5.13B: No Coordination with one dominant path

Figure 5.13: Comparison of Link Queue generated by with and without control strategies for 50% VMS Responsiveness

Link volumes generated by the assigned vehicles are shown in Figure 5.14: Figure 5.14A presents the link volumes generated by the use of control strategies, whereas Figure 5.14B shows link volumes without the use of control coordination. Even though dynamic in nature, link volumes illustrated in Figure 5.14B reach higher values than link volumes presented in Figure 5.14A. Such results may suggest improvement in the traffic conditions experienced on the corresponding links without reaching the break-point capacities.



Link Volume selected; No.2787: 4825->3385; Start Time: 240; End Time: 360; Max Y: 2800

Y-axis unit: Vehicle/hour/lane.

X-axis unit: Minute

Figure 5.14A: R+S with one dominant path **Figure 5.14B: No Coordination with one dominant path**

Figure 5.14: Comparison of Link Volume generated by with and without control strategies for 50% VMS Responsiveness

On the other hand, it should be noted that the contra-flow technique is not fully used in the numerical analysis experimentation adopted in this thesis. This strategy is to be activated along the Baltimore-Washington Parkway (freeway), where three out of the four lanes are to be transformed into outbound lanes towards the safe area. In doing so, one of the two inbound lanes towards the imapcted area are to be converted into an outbound lane towards the safe zone. All the upstream nodes along the links on this path may be converetd into downstream nodes and viseversa. Contra-flow measures can be adopted along with ramp metering and signalization in a coordinated manner. This approach, however, did provide the improvement expected by the author: contra-flow links are partially generated along the I-295 freeway (Path 1) starting from the I-495

Beltway and ending at mid-point between Washington DC and Baltimore (Zone 111). Such modification in the network geometry with sudden change in capacity (number of lanes) serving each traffic direction may not be suitable for real-time dynamic coordination without the construction of additional entry and exit freeway infrastructure. Moreover, with a simulation time limited to a six-hours period, the contra-flow strategy may be more useful for longer intervals of time (one or two days evacuation simulation) for different types of extreme conditions (i.e.: hurricane evacuation).

CHAPTER 6 - CONCLUSIONS

6.1. Concluding Remarks

The objective of this thesis is to offer a dynamic integrated control strategy that can respond in real-time to changes in the demand and the supply during extreme conditions. This strategy relies on the dominant path concept introduced by Abdelghany et al., (1999): the critical paths having highest priorities are identified dynamically and accordingly the evacuation problem can be transformed to an integrated multi-corridor management problem. The control methods coordinated along the corresponding corridors are existing controls already found in the network for an easier real-time implementation: ramp metering, actuated signalization and variable message signs. Contra-flow can be used in a network dependent practical manner.

The formulated coordinated control system is illustrated on the Maryland CHART network. An extreme condition impacts 11 zones in North-East Washington DC (Zones 10, 29, 30, 31, 33, 34, 35, 36, 37, 40 and 41) from 12 noon until 2 pm. During these two hours, these zones need to be evacuated to a safer rural zone (111) along the Washington-Baltimore corridor. The loading demand period is between 8 am until 2 pm. The system adopted caused a clear reduction of trip time and stop time for the impacted vehicles that were diverted through the variable message sign technique. However, this reduction is not translated for all the vehicles as expected.

As discussed in the previous chapter, some promising results are found as a decrease in the average trip time and average stop time for the impacted vehicles in different scenarios is observed. All scenarios are compared in order to find the scenario with the highest improvement, in terms of average trip time and average stop time. In doing so, three main scenarios are illustrated.

- Scenario run with ramp metering and signalization with 50% of VMS responsiveness and when one dominant path is used:
  - The maximum percentage decrease in the average travel time for the impacted vehicles is 9%.
  - The maximum percentage decrease in the average stop time for the impacted vehicles is 74%.
- Scenario run with ramp metering and signalization with 75% of VMS responsiveness and when one dominant path is used:
  - The maximum percentage decrease in the average travel time for the impacted vehicles is 8%.
  - The maximum percentage decrease in the average stop time for the impacted vehicles is 74%.
- Scenario run with ramp metering and signalization with 100% of VMS responsiveness and when one dominant path is used:
  - The maximum percentage decrease in the average travel time for the impacted vehicles is 5%.
  - The maximum percentage decrease in the average stop time for the impacted vehicles is 73%.

In conclusion, the scenario with ramp meters and signalization with 50% VMS responsiveness using one dominant path may be suggested as feasible evacuation option.

6.2. Future Research Need

Although the results are promising, this research focuses on the control aspect for one mode of transportation. This may explain the modest levels of improvements for the average trip time measures. As an example, transit systems can be utilized during the evacuation conditions with better lane usage and with further adoption of contra-flow measures. Moreover, additional calibration and validation effort can be invested in the research for further numerical analysis.

In summary, the future research needs can take several directions:

1) Testing the results on additional networks.
2) Modifying the demand levels to have more congested networks with evacuation strategies tested at different times of day (peak hour PM, peak hour AM), midnight attacks etc.
3) Looking into the role of information provision and departure time choice for added improvement in the measure of effectiveness chosen in the study.

REFERENCES

1) Abdelghany, K. F., D. M. Valdes, A. S. Abdelfatah and H. S. Mahmassani, (1999), Real-time Traffic Assignment and Path-based Signal Coordination, Application to Network Traffic Management. Transportation Research Record, No. 1667, pp.67-76.
2) Alsnih, R. and Stopher, P. (2003). A Review of the Procedures Associated With Devising Emergency Evacuation Plans. Transportation Research Record No. 1865, pp. 89–97.
3) Balakrishna, R., Wen, Y., Ben-Akiva, M., and Antoniou, C. (2008). Simulation-Based Framework for Transportation Network Management in Emergencies. Transportation Research Record No. 2041, pp. 80-88.
4) Brunsma, D.L., Overfelt D., and Picou J.S. (2007). “The Sociology of Katrina, Perspectives on a Modern Catastrophe”. Roman and Littlefield Publishers Inc.
5) Chen, X. (2003). Agent-based Simulation of Evacuation Strategies Under Different Road Network Structures. Texas Center for Geographic Information Science. Department of Geography, Southwest Texas State University.
6) Chen M., Chen L., and Hooks, M. (2007). Traffic Signal Timing for Urban Evacuation. Journal of Urban Planning and Development, American Society of Civil Engineers. Record No. 133 pp. 30-42.

7) Chen A, H. Yang, HK. Lo, and WH. Tang. (1999). A capacity related reliability for transportation networks. Journal of Advanced Transportation. Record No. 33(2), pp. 183-200.

8) Davis E.L, Rough J., Cecchine G., Schaefer A.G and Zeman L.Z. (2007). "Hurricane Katrina: Lessons for Army and Operation". RAND Cooperation, Arroyo Center.

9) Dixit, V. V., S. RAMASAMY and E. Radwan, (2008), Assessment of I-4 Contra-flow Plans: Microscopic vs. Mesoscopic Simulation. National Research Council (U.S.). Transportation Research Board Meeting (87th: 2008 Washington, D.C.).

10) Fu, H. and Wilmot, C. (2004). A Sequential Logit Dynamic Travel Demand Model for Hurricane Evacuation. Transportation Research Record No. 1882, pp. 19-26.

11) Hamdar, S. H. (2004). Towards Modeling Behavior under Extreme Conditions. Master Thesis submitted to faculty of the Graduate School of the University of Maryland, College Park in 2004.

12) Hamdar, S. H., Mahmassani, H.S., and Eisenman, S.M (2005). Evaluation of Operational Strategies for Integrated Corridor Managemen. National Research Council (U.S.). Transportation Research Board Meeting (85th: 2006 Washington, D.C.).

13) Hamdar, S. H., Zhang, Mahmassani, H. S. and K., Khan, M. Z (2010). A Real – Time Coordinated Control System for Emergency Evacuation. First National Evacuation Conference, New Orleans, Louisiana, 2010.

14) Hobeika, A. G., and C. Kim. (1998). Comparison of traffic assignments in evacuation modeling. IEEE Transactions on Engineering Management. Record No. 45(2), pp. 192-98.

15) Horne J., (2008). “Breach of Faith: Hurricane Katrina and the Near Death of a Great American City”. Random House Trade Paper Back Edition.

16) Kwon, E., and Pitt, S. (2005). Evaluation of Emergency Evacuation Strategies for Downtown Event Traffic Using a Dynamic Network Model. Transportation Research Record: Journal of the Transportation Research Board Record No. 1922, pp. 149-155.

17) Lam, C. P., Brown, C., Slyke C. V., and Wang. H. Applying Mesoscopic Simulation to Evacuation Planning for the Houston Region.

18) Lam, WHK, and G. Xu. (1999). A traffic flow simulator for network reliability assessment. Journal of Advanced Transportation Record No. 33(2), pp. 159-82.

19) Mahmassani, H.S., Sbayti, H.A. and Zhou, X.(2004). *DYNASMART-P Version 0.930.7 User’s Guide.* Prepared for U.S. Department of Transportation.

20) Mclaughlin., E. C. (August 2006), “A year later, recovery in New Orleans not easy” http://www.cnn.com/2006/US/08/28/katrina.anniversary/index.html (seen in February 2010)

21) Mollaghasemi, M., Aty, M. A., and Yu, J. W. An Integrated Emergency Management Decision Support System for Evacuation. Project ID # 46. University of Central Florida.

22) Papageorgiou M., H. Haj-Salem, and F. Middelham (1998). ALINEA Local Ramp Metering: Summary of Field Results. In Transportation Research Record: Journal of the Transportation Research Board Record No. 1603, pp. 13-20.

23) Quiroga, CA. (2000). Performance measures and data requirements for congestion management systems. Transportation Research Part C-Emerging Technologies Record No. 8(1-6), pp. 287-306.

24) Russo, F., and A. Vitetta. (2002). Models and algorithms for evacuation analysis in urban road transportation systems. In Pedestrian and evacuation dynamics eds. M. Schreckenberg and S. D. Sharma. Verlag, Berlin, Heidelberg, New York: Springer.

25) Southworth, F. and Chin, S. (1987). Network Evacuation Modelling For Flooding As A Result of Dam Failure. Environment and Planning A, Record No. 19 (11), pp. 1543-1558.

26) Shekar, S., and Kim, S. (2006). Contraflow Transportation Network Reconfiguration for Evacuatoin Route Planning. Department of Computer Science, University of Minnesota. Published by Minnesota Department of Transportation, MDOT.

27) Wolshon, B., Urbina, E., and Levitan, M. (2002). National Review of Hurricane Evacuation Plans and Policies. Technical report, Hurricane Center, Louisiana State University, Baton Rouge, Louisiana.

28) Yaun, F., Han, L. D., Chin. S., and Hwang, H. (2006). Proposed Framework for Simultaneous Optimization of Evacuation Traffic Destination and Route Assignment. Transportation Research Record.

29) Yang, Q., H. N. Koutsopoulos, and M. E. Ben-Akiva. Simulation Laboratory for Evaluating Dynamic Traffic Management Systems. Journal of the Transportation.