Real-Time Variable Message Signs Based Route Guidance Consistent With Driver Behavior

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ABSTRACT

Variable Message Signs (VMS) represent a cost-effective mechanism for disseminating information to drivers unequipped to receive personalized information. They can be used under incidents to divert traffic to less congested areas of the network to circumvent lengthy queues, better utilize network capacity, and improve system performance. This paper proposes and evaluates a VMS control heuristic framework that seeks diversion under incidents to enable a traffic system controller to favorably control traffic conditions in real-time. The framework ensures consistency with driver diversion response behavior, is responsive to changing traffic conditions, enables computational tractability through stage-based on-line implementation, and ensures the spatial and temporal consistency of the displayed messages. It uses a hybrid framework that consists of off-line and on-line components to determine the VMS messages. The ability to display messages that are consistent with driver diversion behavior represents a valuable tool for the controller to enhance system effectiveness by simultaneously satisfying system-wide and individual user objectives. Real data on driver VMS response attitudes from the Borman Expressway corridor in northwestern Indiana and simulated experiments are used to derive insights on the practical effectiveness of the proposed VMS control heuristic.

INTRODUCTION

Variable Message Signs (VMS) are electronic message boards located in close proximity to roadways. They represent a cost-effective mechanism for disseminating information to drivers unequipped to receive personalized real-time routing information and/or guidance. Hence, unequipped drivers can be directly influenced through VMS messages. VMS enable traffic controllers to inform drivers in real-time about changing traffic conditions, and are commonly used for parking guidance, control of high occupancy vehicle (HOV) lanes, safety warnings, and flow diversion. This paper focuses on their potential use under incidents. Though VMS have been implemented in practice for the above-mentioned uses, their effective use for route guidance has not fully matured. Existing VMS route guidance algorithms are typically network specific and hence lack portability. A key issue is their inability to display messages that are consistent with driver diversion response attitudes for that traffic network. Such a capability is critical for the system controller to enhance network performance while ensuring increased acceptability of the suggested guidance and improving the credibility of VMS information among drivers. Also, most algorithms have limited capabilities to dynamically reflect changing traffic conditions, especially under incidents. The displayed messages tend to be static or quasi-dynamic with a fixed frequency of message updates. Thereby, they cannot vary the message update frequency as warranted by the changing traffic conditions to optimize system performance. In addition, they do not address the important operational issue of which VMS to activate for a particular traffic scenario, as activating all of them may not represent the best strategy. An additional practical challenge is the need to ensure spatial and temporal consistency among the displayed messages. The current algorithms typically cannot be deployed in real-time

either due to the lack of a suitable on-line framework or computational efficiency to meet real-time constraints.

This research proposes to use VMS message content (in terms of the amount of information disseminated) as a control variable to influence route diversion and seek consistency with driver behavior. As per the approach, the message contents of the activated VMS are such that the diversion rates generated by the VMS response attitudes of the drivers closely match those desired by the system-wide objectives of the controller. In this context, a VMS control heuristic is developed that determines the VMS to be activated, the messages to be displayed, and when messages need to be updated. It is computationally tractable on-line, consistent with driver behavior, responsive to changing traffic conditions, portable, and obviates the need for long-term future demand and/or system state predictions. The associated implementation framework uses a hybrid combination of off-line and on-line components to determine the diversion rates that would optimize system performance under an incident. It then uses a driver VMS route diversion response behavior model previously developed by the authors (*1*) to determine the content of messages to be displayed consistent with the desired diversion rates.

LITERATURE REVIEW

Currently, VMS are used primarily to provide information on ambient traffic and/or weather conditions, manage traffic in work zones, control access to HOV lanes, display safety messages, and notify drivers about public events. Hence, their locations may not be ideal from the perspective of motorist information needs (*2*). The strategic location of VMS in the network is an important consideration because it gives the traffic manager better control over the system compared to rule-of-thumb based location approaches. Genetic algorithm based approaches have

been proposed (*3*) to determine the strategic locations of VMS. This study assumes the VMS locations to be known.

Field studies suggest that route guidance using VMS has the potential to improve system performance more effectively compared to VMS displaying traditional descriptive information like current weather conditions, congestion levels, and HOV lane access control. Field tests conducted in the city of Aalborg, Denmark (*4*) used an automatic control strategy based on real-time loop detector measurements for VMS-based route guidance. It included a simple rule for computing travel times. The study results suggest perceptible improvements to the system performance. Studies were also conducted on the 600-km freeway network around Paris (*5*), aimed at modifying individual driver behavior to improve system performance. Link flow evaluations using loop detector data were performed to estimate flow rate differences with and without VMS. Also, traffic flow data analysis was performed for a selected link to analyze user response variation with the VMS message type.

A common drawback of the above studies is their opaqueness to driver attitudes to displayed VMS messages (*6*). It is important to consider the interactions between the drivers and the displayed messages to enhance the effectiveness of VMS-based control strategies. A significant factor influencing VMS driver response is the perception of the reliability of the displayed messages. Frequent changes to the displayed messages, inconsistent messages on consecutive message signs, and/or route prescriptions that lead to perceived unfavorable experiences adversely affect this perception and consequently the system performance due to reduced compliance. Driver attitudes are further affected by on-line traffic conditions and other situational factors such as time-of-day and weather conditions (*1*), highlighting the fixed-point interaction between driver response and network performance.

Existing VMS algorithms typically lack generality and address specific networks, primarily to study driver response to VMS messages and estimate the system performance for specific incidents. A key objective of the proposed research is to develop a framework that is general in its scope of application. A recent effort (*7*) to generalize the VMS solution determines the optimal route diversion rates using a multiple user classes dynamic traffic assignment model (*8*) under the system optimal objective. These diversion rates are targeted through VMS message display. However, the approach does not incorporate a mechanism by which the desired diversion rates can actually be achieved consistent with driver VMS response attitudes. It provides individual drivers personalized optimal routes to their destinations through VMS by comparing the current path with the new diversion path and using a switching threshold. This is operationally infeasible since VMS are constrained to display generic messages and cannot provide information on specific routes. It also implies that the VMS display information on incident-induced delays. The approach is used until five minutes after incident clearance, after which the VMS are assumed to be deactivated. It also assumes that all drivers, equipped or unequipped, who pass by a VMS are affected by the displayed information identically from a behavioral perspective. It discounts the possibility that equipped drivers may weigh personalized information more than the generic VMS message.

This study has some similarities with (*7*) in that a dynamic traffic assignment (DTA) model (*8*) is used to determine the desired diversion rates. However, the underlying mechanism to determine these diversion rates is different. Also, unlike (*7*), message content is a variable that is used to seek consistency between system objectives and driver response behavior. Information on incident-induced delays is only one of the many possible VMS message contents considered for display under an incident. Lesser or greater amount of detail on the incident and/or guidance is used to generate different diversion rates through VMS (*1*). The proposed approach updates

VMS messages based on the current incident status and ambient traffic conditions. Thereby, the message update frequency is a variable and the displayed message content can change with time. Hence, a VMS may be deactivated before or substantially after incident clearance. The study assumes that equipped drivers are not influenced by the VMS and follow personalized paths specified by an information service provider. While reasonable, this assumption can be behaviorally limiting because equipped drivers may use both personalized and generic (VMS) information to make diversion decisions. However, the proposed approach is not limited by this assumption as it uses current traffic flow measurements to determine the desired diversion rates. Also, it can incorporate more general behavioral models vis-a-vis response to information for equipped drivers.

PROBLEM STATEMENT

Given a traffic network G(N,A), with $n \in N$ nodes and $a \in A$ arcs, user class fractions, variable message signs at pre-specified locations, a VMS driver diversion response model (*1*), and an incident clearance time prediction model (*9*), the traffic system controller seeks to determine the time-dependent VMS messages to be displayed during the horizon of interest (typically under incidents) that address some system-wide objectives and are consistent with driver VMS response behavior. Implicit in this problem is the usage of message content as a control variable to achieve the desired diversion rates. The problem consists of determining: (i) the VMS to be activated for message display, (ii) the messages to be displayed, and (iii) the frequency at which messages should be updated, so that unequipped drivers diverting based on their VMS diversion response attitudes satisfy some system-wide objectives of the traffic controller. The user class fractions are based on unequipped and equipped drivers. However, equipped drivers may further

be categorized into classes such as user equilibrium (UE) objective drivers and system optimal (SO) objective drivers.

METHODOLOGY

Overall Approach

Figure 1 illustrates the overall approach for determining the VMS messages that are consistent with the desired diversion rates and driver VMS response behavior. An incident triggers the incident clearance time prediction model (*9*) which estimates the time to incident clearance. The current traffic conditions on the network are obtained from the traffic control center (TCC). The VMS control heuristic is activated to determine the desired diversion rates that satisfy some system-wide objectives of the controller. For the various VMS to be activated according to this heuristic, the message contents that generate the closest match between the desired diversion rates and the diversion rates obtained from the VMS driver response model (*1*) for that network are used to determine the messages to be displayed. The VMS control heuristic is used to determine when messages should be updated. The procedure ends when all VMS are deactivated.

VMS Driver Response Model

The VMS driver response model (*1*) determines the probability of diversion in response to different VMS message contents. It is developed using data from a stated preference (SP) survey in the associated network. Logit models are developed for drivers' diversion decisions. Table 1 illustrates the relationship between VMS message content and the propensity to divert for a SP

survey conducted in the Borman Expressway corridor in northwestern Indiana. The responses were recorded on a five point Likert scale, where 1 meant low willingness to divert and 5 meant high willingness to divert. The analysis suggests that content in terms of the level of detail of relevant VMS information significantly affects the willingness to divert. Hence, different diversion rates can be induced using different message contents. The SP survey (*1*) revealed that other significant factors influencing VMS route diversion decisions include socioeconomic characteristics (gender, age, education level, and household size), network spatial knowledge (regular driver in the region, familiarity with alternative routes), trip type (work or non-work), amount of delay, and confidence in the displayed information. Detailed descriptions of the survey design, dependent variables, and the VMS driver response models are provided in (*1*).

VMS Control Heuristic

The VMS control heuristic determines the optimal diversion rates at the various activated VMS for unequipped drivers under current network conditions. Its primary objective is to obtain new path assignment proportions for unequipped drivers whose initial paths (historical paths) include the incident link. In the absence of any information, these drivers follow their initial paths. However, VMS upstream of the incident link can be used to divert them from these paths by providing routing information that aids incident management.

The VMS control heuristic ensures that the VMS are inactive before an incident and after the effects of an incident have dissipated. It uses the VMS driver response model to determine the messages to be displayed. The VMS locations to be activated are determined by comparing diversion rates with threshold activation criteria. Messages are updated based on traffic data and incident clearance status feedback. The VMS control heuristic consists of three sub-algorithms

that follow a sequential logic to determine: (i) the VMS that should be activated, (ii) the messages to be displayed on the active VMS, and (iii) when the VMS messages should be updated. The sub-algorithms are as follows:

The Activation Algorithm

The Activation algorithm uses a set of heuristic rules to determine the VMS to be activated for displaying messages. These rules activate only those VMS for whom the required diversion rates to improve system performance exceed a pre-specified threshold. This eliminates the need to activate VMS which do not significantly influence system performance. This aspect is computationally attractive from an operational standpoint.

The algorithm scans all origin-destination (O-D) pairs in the network to identify incident-affected paths. From this set, the K most used paths, in terms of path flows, between each O-D pair that include the incident link are identified. Any VMS on these paths are activated if they satisfy at least one of the following activation criteria: (i) VMS is within R minutes of incident link, and (ii) VMS is within Y miles of the incident. Here, R and Y are pre-determined parameters for that network.

The K most used paths that include the incident link are obtained using current network data. R is determined using the time-dependent path travel times and is a more robust filter criterion than Y because it better reflects the ambient traffic conditions. It could, for example, be a percentage of the path travel time from the origin node to the upstream node of the incident-affected link, or a measure based on the predicted incident clearance time. It can be time-dependent to reflect improvements in the network performance due to the VMS strategies adopted in previous intervals, and hence enhances the efficiency of the VMS control heuristic. While the use of Y is less meaningful in congested situations, it can be a useful threshold in the

absence of time-dependent network data. Also, it is useful when addressing incidents involving hazardous material spills which require the quarantine of a region.

The Message Display Algorithm (MDA)

The Message Display algorithm, illustrated in Figure 2, determines the messages to be displayed on the activated VMS based on the system controller objectives. In the figure, T denotes the length of the planning horizon. A multiple user classes deterministic DTA algorithm (*8*), (*10*), is used to determine the optimal path assignment proportions under the incident based on the SO objective while assuming that all drivers, including the unequipped ones, are SO drivers (case 1). This represents the benchmark for the best system performance under that incident. The path assignment proportions are also computed under the incident based on the SO objective using the actual user class fractions (case 2). The path assignment proportions from the two scenarios are used to determine the desired diversion rates, and consequently the messages to be displayed on the VMS. This is done by comparing the path assignment proportions from case 2 with the *desired* path assignment proportions from case 1. If the proportions are larger in case 2 compared to case 1 for the incident-affected VMS paths, unequipped users could be induced to switch from those paths through appropriate VMS messages. Hence, the objective of the MDA is to seek the network flow pattern under case 1. The percentage diversions of unequipped drivers from the VMS links represent the desired diversion rates. However, a single VMS may lie on different paths requiring different diversion rates. Since only one message can be displayed on the VMS for all such paths, a combined measure of these diversion rates has to be considered for operational purposes. From the limited experiments conducted in this study, an average of these diversion rates represents a good proxy for the desired diversion rate. The diversion rate from the VMS driver response model that is closest to the desired diversion rate for a particular VMS is used to determine the message to be displayed.

The Update Frequency Algorithm

The displayed VMS messages need to be updated over time to reflect changes in the incident situation and/or traffic flow conditions. For example, progress in incident clearance may increase capacity on the incident link leading to an increased ability to route traffic through the incident area. Similarly, improved traffic conditions in the vicinity of the incident due to prior VMS messages may require the updating of the messages displayed. The Update Frequency algorithm determines when such updates should occur (that is, when to invoke the MDA). It does so by monitoring at regular intervals the incident clearance status and the flow conditions in the incident vicinity. The length of the monitoring interval depends on the specific network and the incident status. Hence, the Update Frequency algorithm can aid the efficiency of the VMS control heuristic and its effectiveness vis-à-vis system performance. The logic of the Update Frequency algorithm is as follows:

Incident Link: If the incident link capacity in the monitoring interval τ is α% different from that of interval (τ-1), where α is a pre-set time-dependent threshold, the MDA is invoked.

Ambient Traffic Conditions: If the incident link conditions do not warrant an update, the ambient traffic conditions in its vicinity are analyzed by computing the updated instantaneous path travel times on the K most used paths from each origin node to the incident link upstream node. If the difference in the path travel times for β of these paths in two successive monitoring intervals exceeds γ%, the MDA is invoked. Here, β and γ are pre-specified thresholds.

If neither update criteria trigger an update, the current messages are retained. Incident clearance time prediction models (*1*), (*9*) are used to estimate the remaining incident clearance time and project when the messages are likely to be deactivated.

VMS Control Heuristic Implementation

The proposed VMS control heuristic is implemented using a hybrid framework (*11*) consisting of off-line and on-line components. The off-line component addresses the computationally intensive aspects and the on-line component uses an efficient rolling horizon implementation that circumvents future state predictions. The rolling horizon implementation is ideal from the perspective of on-line deployment (*8*) because of the computational time savings obtained by using a truncated planning horizon.

Off-line component: The computationally intensive off-line component determines the benchmark time-dependent SO path assignment proportions using a deterministic DTA algorithm for several probable incident scenarios and a mean O-D demand. These sets of path assignment proportions are stored for use by the on-line component to determine the desired diversion rates in a computationally efficient manner.

On-line component: Figure 3 illustrates the rolling horizon implementation of the VMS control heuristic. It is a stage-based approach illustrating the on-line nature of the VMS control heuristic. A stage is a truncated portion of the planning horizon, implying lesser computational effort. The planning horizon is divided into several stages. If an incident and/or high congestion is detected in the current stage the VMS control heuristic is executed to determine the desired diversion rates and the messages to be displayed in the next stage. In the absence of incidents and/or high congestion, the deterministic DTA model is used to determine the optimal path assignment proportions. The current stage is incremented and the messages determined in the previous stage are implemented for a roll period, which is a sub-interval of a stage. The network data collected from detectors is used to repeat this process in the next stage.

Figure 4 illustrates a typical cycle of the VMS control heuristic using the rolling horizon framework. The flow of logic in the figure is for the stage i in which the incident is first detected.

It is used to determine the messages to be implemented in stage i+1. The inputs are the predicted O-D desires of drivers departing in this stage and the historical paths for the unequipped drivers. The VMS messages are assumed to influence only the unequipped drivers. The Activation algorithm determines the VMS locations for activation. The Message Display Algorithm determines the message to be displayed by mapping diversion rates onto actual messages through the driver diversion response model *(1),* (*9*).

Figure 5 illustrates the execution of the VMS control heuristic in any stage subsequent to the stage in which the incident is detected. The Update Frequency algorithm is executed for each monitoring interval and is used for updating messages within the current stage using the update criteria. The monitoring interval is a sub-interval of the current roll period. If neither of the update criteria are satisfied the messages remain unchanged.

The control heuristic is repeated until all VMS are deactivated implying that the adverse effects of the incident on the network have dissipated. A computationally attractive feature of this approach is that the MDA is activated only when deemed necessary by the Update Frequency algorithm. Additionally, the parameters in the Update Frequency algorithm can be adjusted to vary the frequency of MDA activation to suit the resources of the traffic controller.

The Consistency Issue

Ideally, the solution generated through the VMS control heuristic is favorable to all drivers since it factors in the diversion of the unequipped drivers. However, temporal and spatial inconsistencies in the messages displayed may arise during the practical implementation of the procedure. They include the display of inconsistent quantitative or qualitative information across

different VMS, both geographically and over time. The successful implementation of the VMS control heuristic requires consistency in the displayed messages.

EXPERIMENTAL ANALYSIS

Simulation experiments were conducted to evaluate the performance of the VMS control heuristic and obtain insights on its characteristics.

Setup

The experiments were conducted using the Borman Expressway corridor network, illustrated in Figure 6, that consists of 197 nodes and 458 links. The Borman Expressway (I-80/94) has a high percentage of truck traffic (ranging from 30-70%). Incidents involving trucks severely affect network performance. Recently, the Indiana Department of Transportation (INDOT) installed an advanced traffic management system (ATMS) on this corridor to enable VMS-based incident management. Several experiments using realistic hypothetical scenarios were simulated to obtain insights on the VMS control heuristic. In all cases, the corresponding system optimal solutions (obtained by assuming all drivers as SO drivers) were used as benchmarks to evaluate the effectiveness of the proposed VMS control heuristic. DYNASMART (*12*), a mesoscopic traffic simulator, was used to conduct the experiments.

As stated earlier, the unequipped drivers are assumed to follow their historical paths in the absence of information. The generic VMS messages are assumed to influence the routing decisions of only the unequipped drivers, and equipped drivers follow the personalized routes specified by the corresponding objective.

Scenario 1: Number of Incidents

This scenario seeks insights on the performance of the VMS control heuristic vis-à-vis the number of incidents. The base case for each experiment is the corresponding benchmark 100% SO drivers solution obtained using the multiple user classes deterministic DTA model (*8*). It represents the best system performance achievable under that experiment. The VMS solution is compared to the base case solution to infer on the effectiveness of the VMS control heuristic.

The experiments in this scenario generate approximately 57000 vehicles in the network over a planning horizon of 35 minutes. All drivers belong to the unequipped class and their initial paths are obtained by randomly assigning them time-dependent k-shortest paths. All experiments consider a 75% reduction in the affected incident link capacity. The incidents start at time 5 minutes and are assumed to be present for a 30 minute duration. In terms of the incident locations, the single incident scenario is on the Borman Expressway (west-bound); the second incident is on I-65 (south-bound and to the south of the Borman); the third incident is on the Borman (east-bound); and the fourth incident is on US-20 (to the north of the Borman.).

Figure 7 illustrates the performance of the VMS heuristic under different numbers of incidents, compared to the no-information case represented by the 100% unequipped drivers solution. Savings ranging from 13-25% are obtained, with the best savings obtained under the two-incident scenario. The savings decrease with increasing number of incidents. This is because more incidents lead to a greater disruption in the traffic flow and hence drivers may benefit more from personalized information compared to generic VMS information.

Figure 8 shows the average diversion rates for the two-incident experiment. They indicate that diverting drivers early on during the incident has substantial benefits in terms of system

performance. Due to the early diversion, there is improvement in network performance which manifests as reduced desired diversion rates towards the end of the incident clearance.

Scenario 2: Incident Duration

Scenario 2 experiments evaluate the performance of the VMS control heuristic with varying incident duration (which is a proxy for incident severity). The incident characteristics are identical to those of the two-incident case in scenario 1, with incidents of 5, 10, and 20 minutes durations. Figure 9 illustrates the performance of the heuristic for the different incident durations. The results indicate increased savings with incident duration suggesting that the VMS heuristic is more effective under more severe incidents. Other experiments suggest that under very severe incidents personalized information and coordinated strategies may be necessary to obtain additional benefits beyond those due to generic diversion because of limited opportunities to gain savings in highly congested networks.

Scenario 3: Congestion Level

These experiments seek insights on the effectiveness of the VMS control heuristic under varying congestion levels. This would enable the system controller to decide whether to deploy the VMS algorithm for different congestion situations. The two-incident case in scenario 1 is used for these experiments. Figure 10 shows the performance of the 100% unequipped case and the VMS heuristic under low to high congestion levels, ranging from average network speeds of 50 km/h to 10 km/h, respectively. At low congestion levels, significant delays are not encountered. Hence, the VMS heuristic performance, while significant (about 40% better than the

corresponding unequipped users scenario), has lesser savings than under medium congestion. Under medium congestion, the delays are significant enough to warrant savings through VMS diversion, further fortified by significant opportunities to switch to less congested paths. Under high congestion, the opportunities to divert drivers to better paths through generic VMS messages are reduced due to high network congestion levels. This is also reflected in the figure.

CONCLUDING COMMENTS

An on-line deployable VMS control heuristic is devised to address the problem of determining the time-dependent VMS messages, display locations, and message update frequencies, to divert unequipped drivers and enhance system performance. The implementation of the VMS control heuristic consists of a hybrid framework of off-line and on-line components with the computationally intensive off-line component contributing to the on-line efficiency of the procedure. The desired optimal path assignment proportions for common incident scenarios can be stored through off-line computation. The key advantage of the VMS control heuristic is its consistency with driver VMS diversion response behavior using message content as a control variable. The Message Display algorithm takes into account the driver diversion response attitudes and the current network conditions to determine the messages to be displayed. Hence it can potentially display different messages for similar desired diversion rates under different ambient network conditions (time-of-day, weather conditions, etc.). The proposed heuristic is also practically feasible as it determines a single message to be displayed by averaging desired diversion rates. Simulation experiments highlight the effectiveness of the VMS control heuristic under alternative real-world type scenarios.

The assumption that equipped drivers ignore the VMS messages and follow personalized routes can be behaviorally limiting as they may make route diversion decisions using both personalized and VMS information. From an operational perspective, the temporal and spatial consistency of the displayed messages should be ensured for the credibility of the VMS-based incident management. These issues represent future research directions.

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LEGEND

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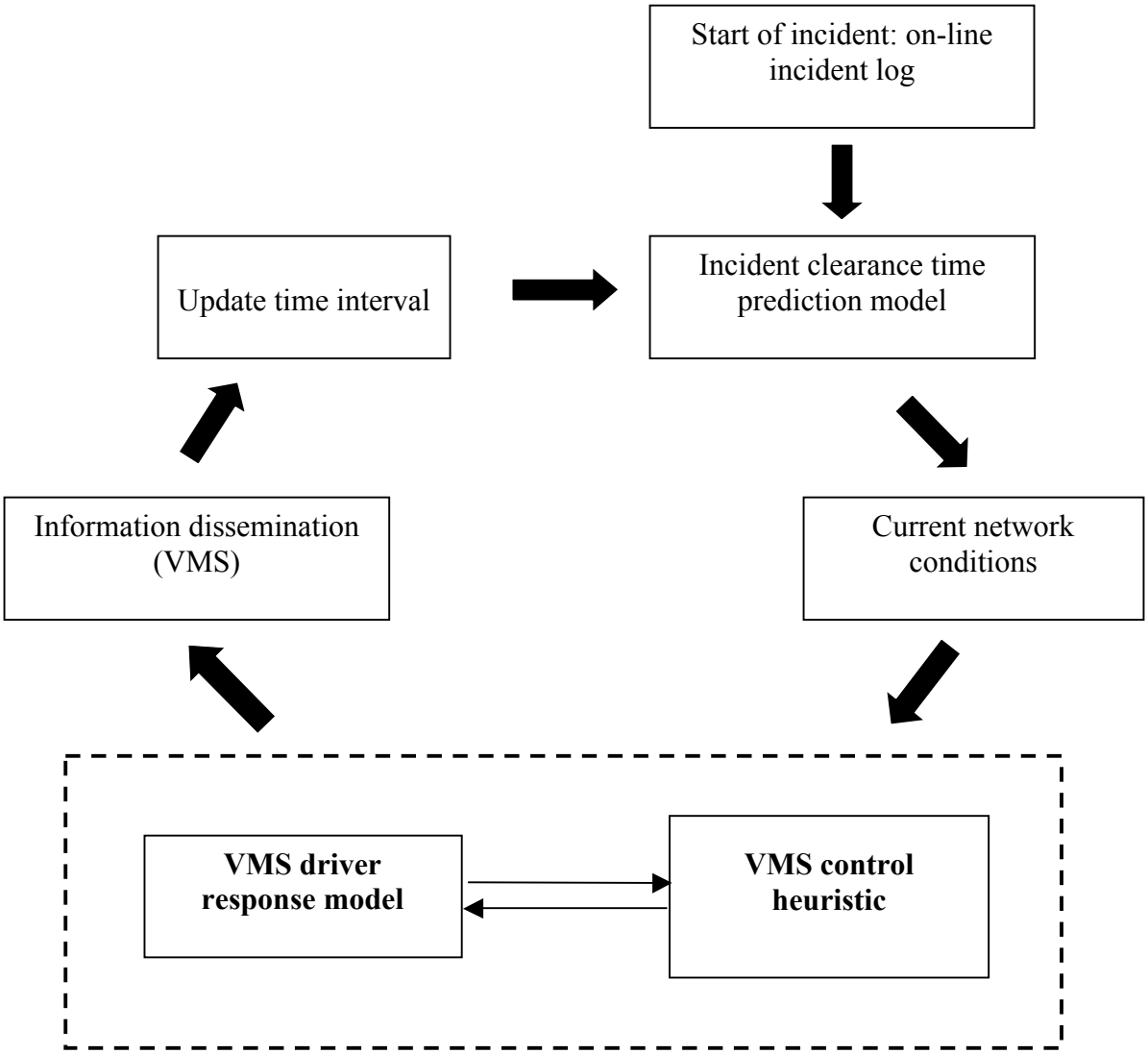

FIGURE 1 Overall approach.

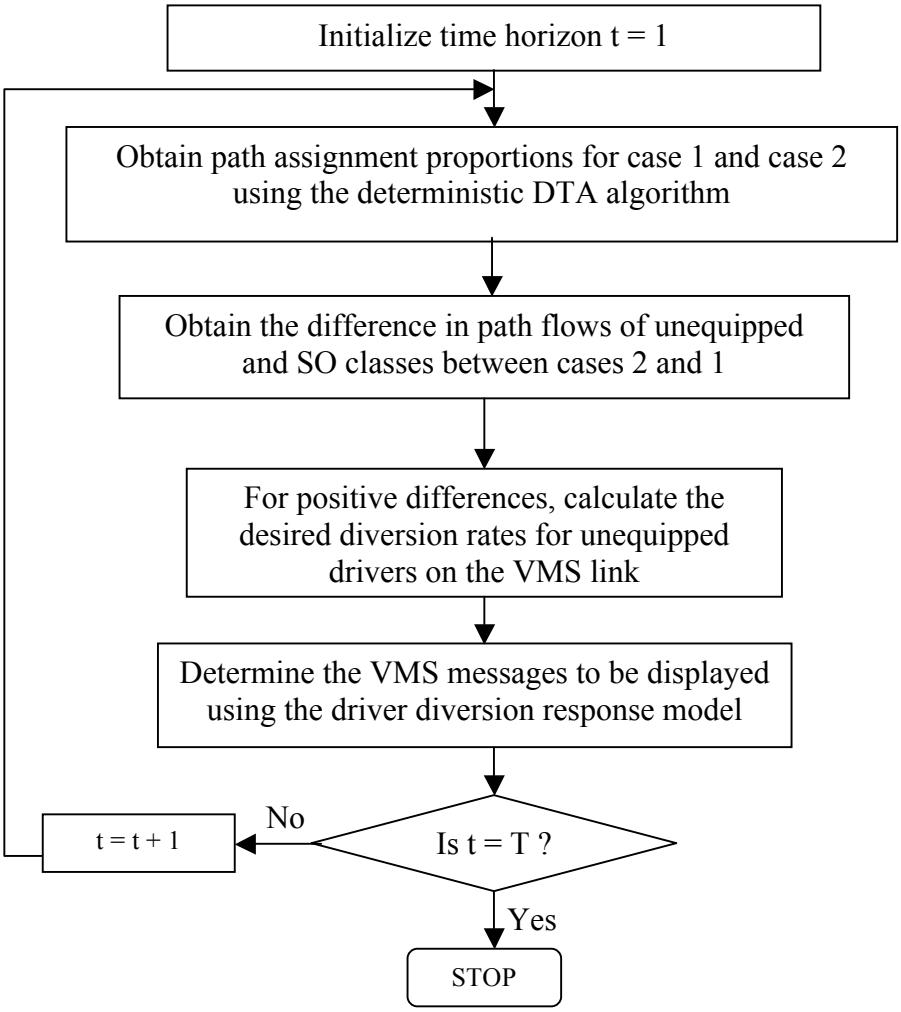

FIGURE 2 Message display algorithm.

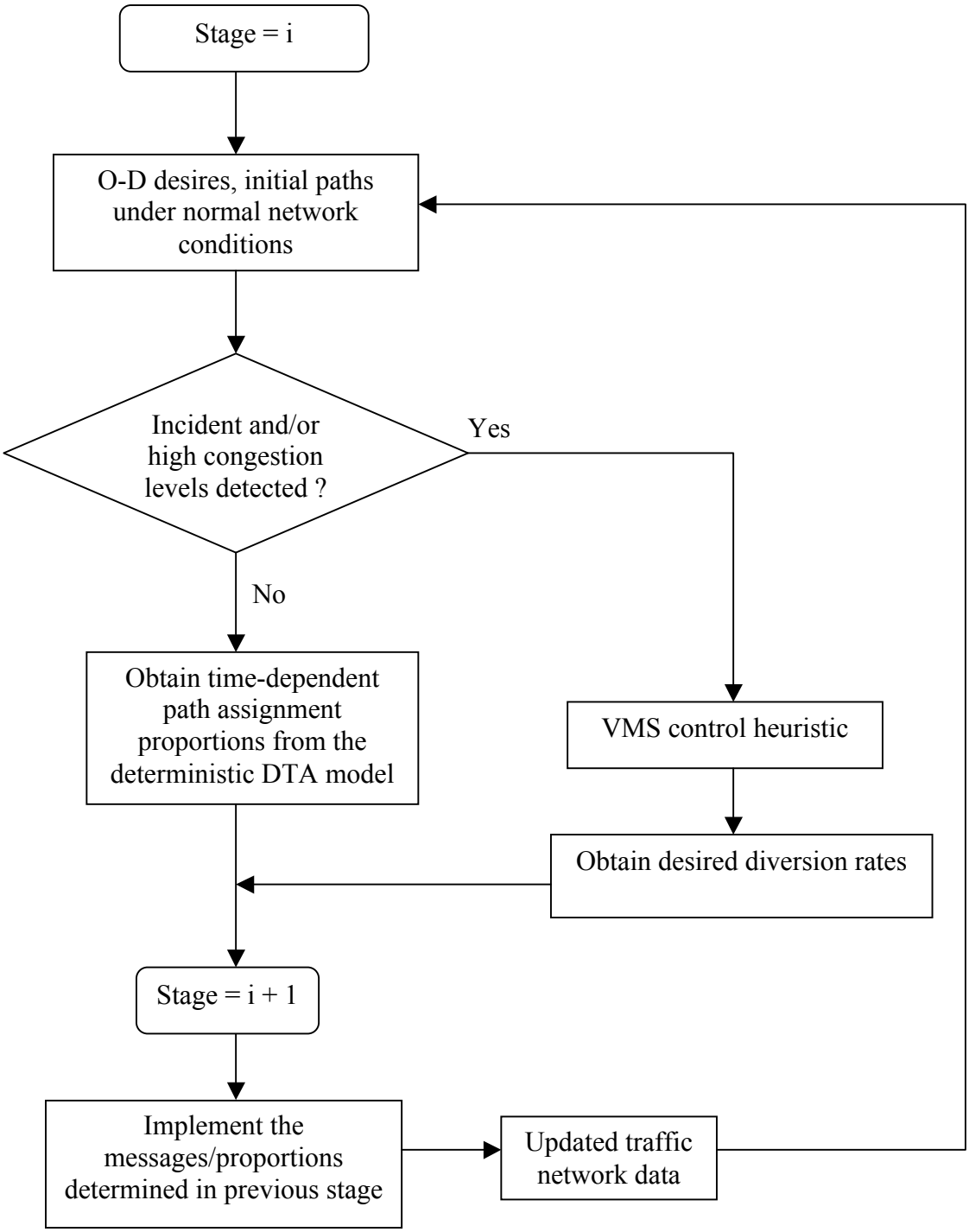

FIGURE 3 Rolling horizon implementation.

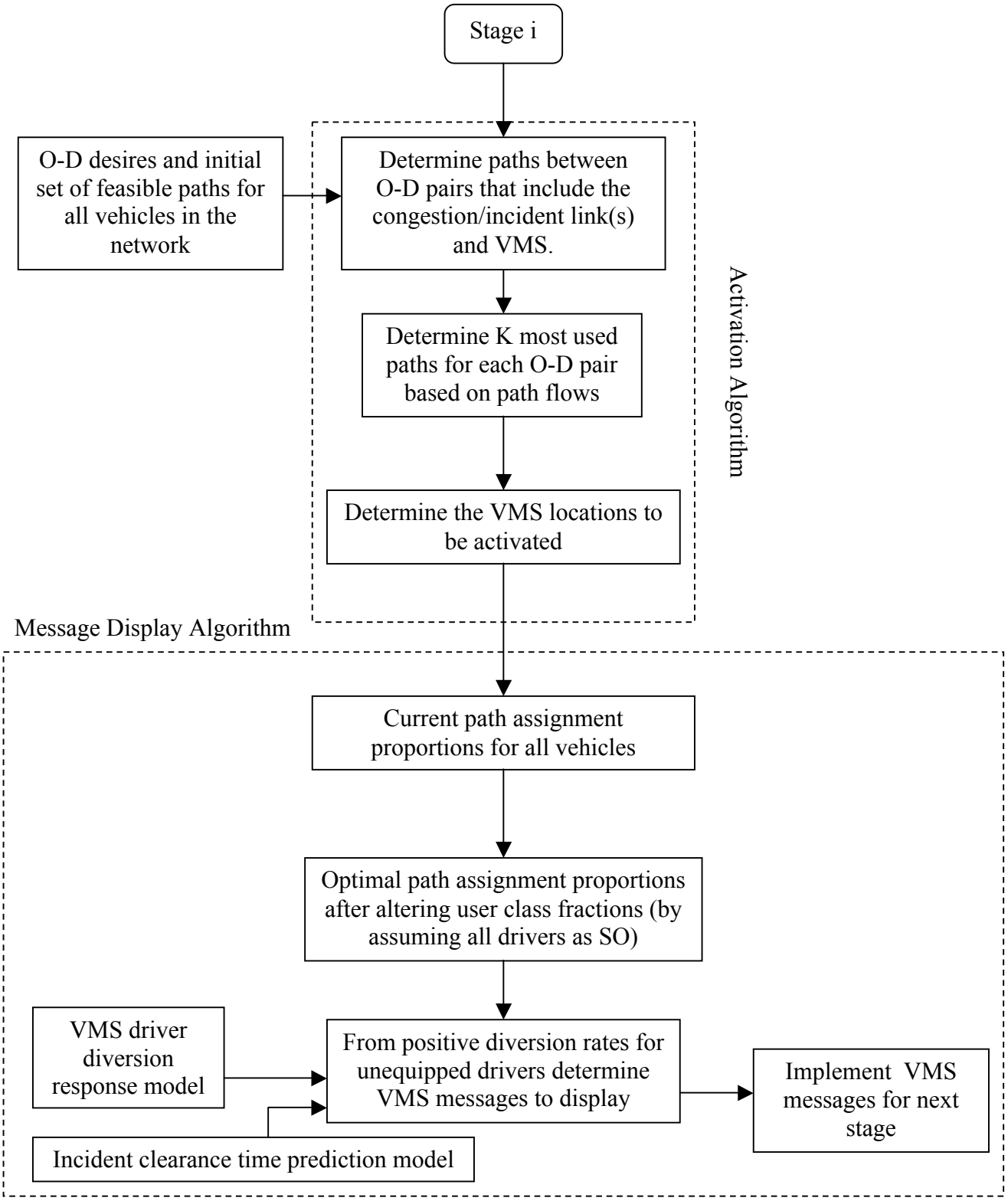

FIGURE 4 The rolling horizon implementation of the VMS control heuristic in the stage that the incident is first detected.

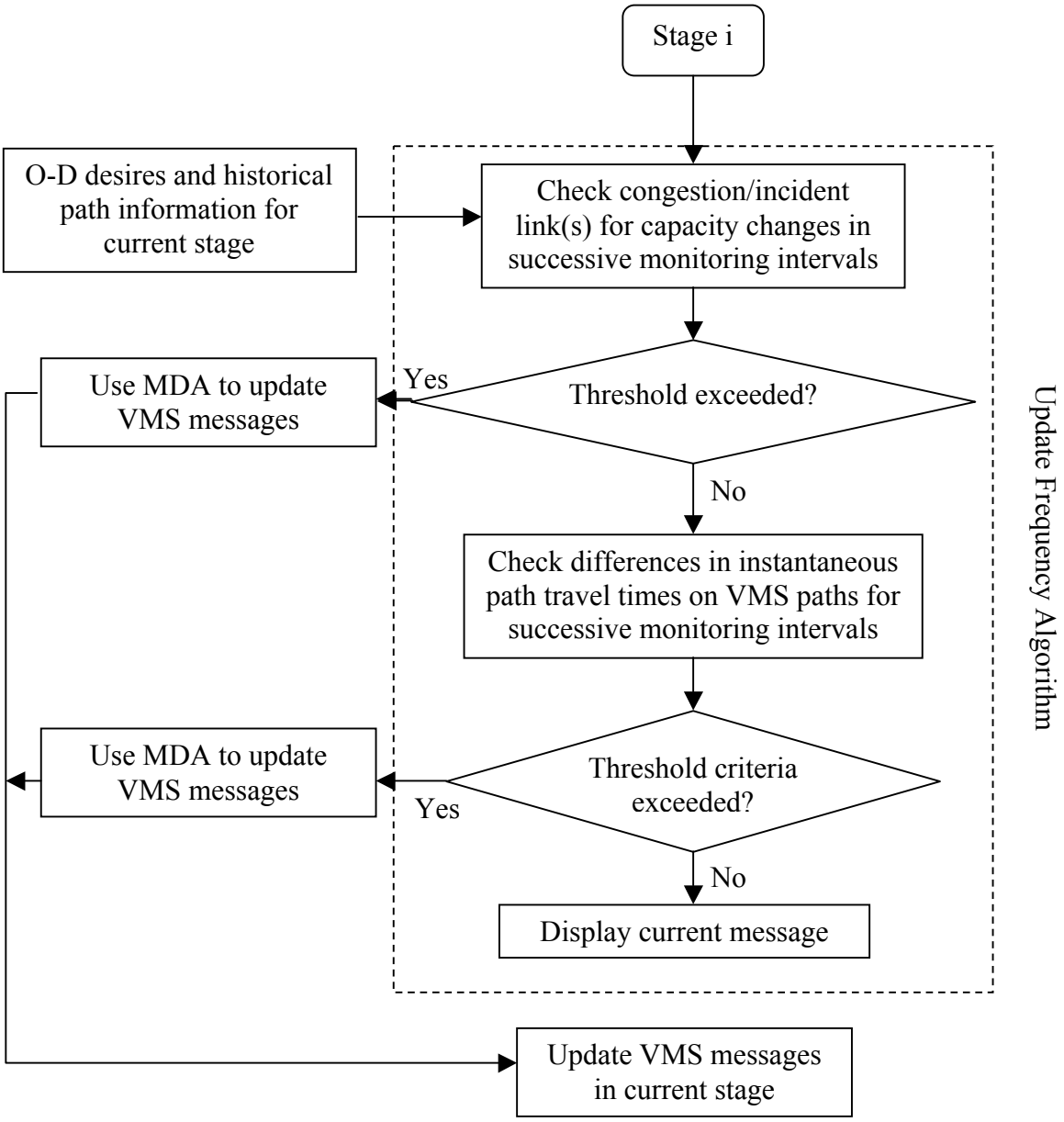

FIGURE 5 The rolling horizon implementation of the VMS control heuristic in stages following the detection of the incident.

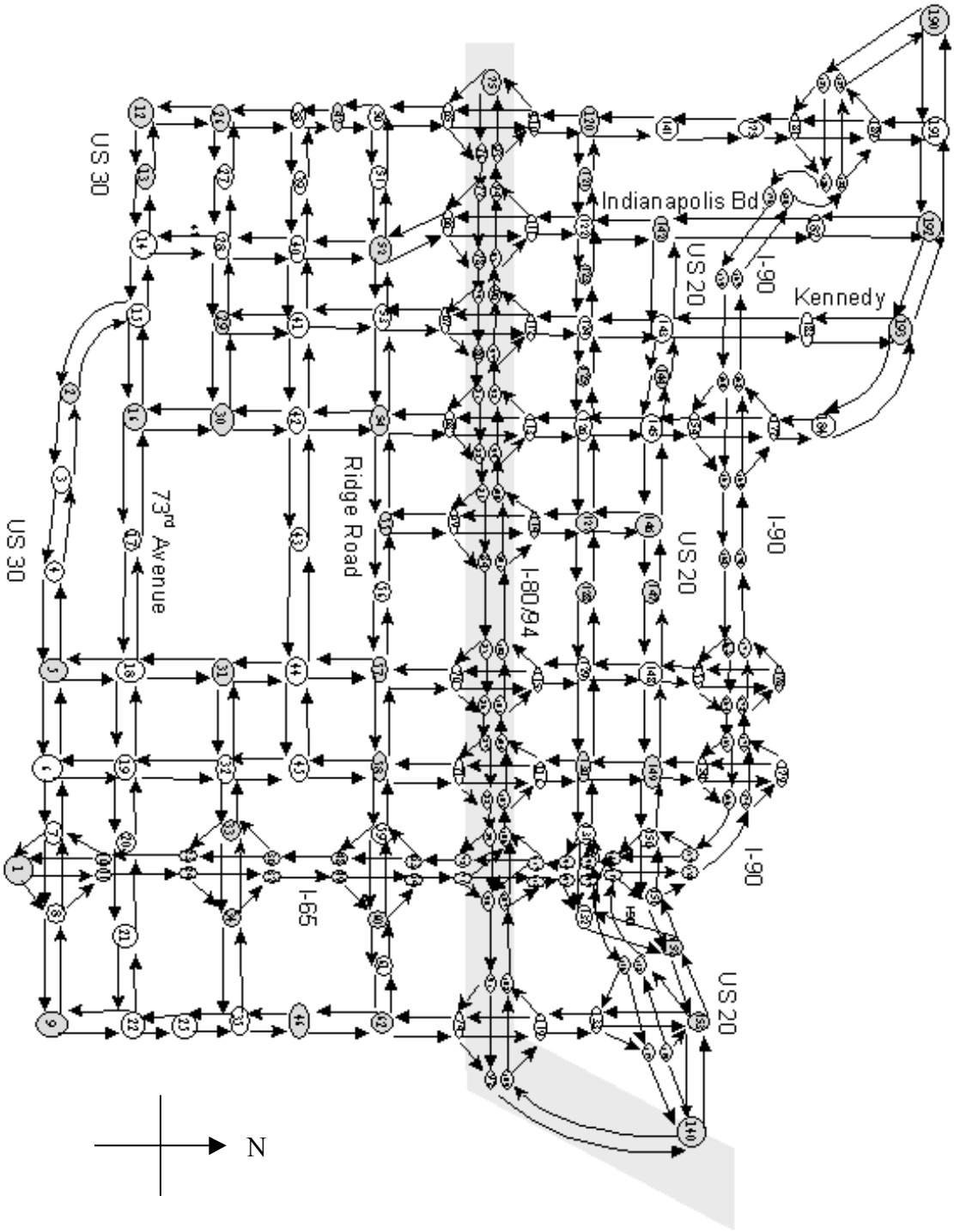

FIGURE 6 Borman expressway network.

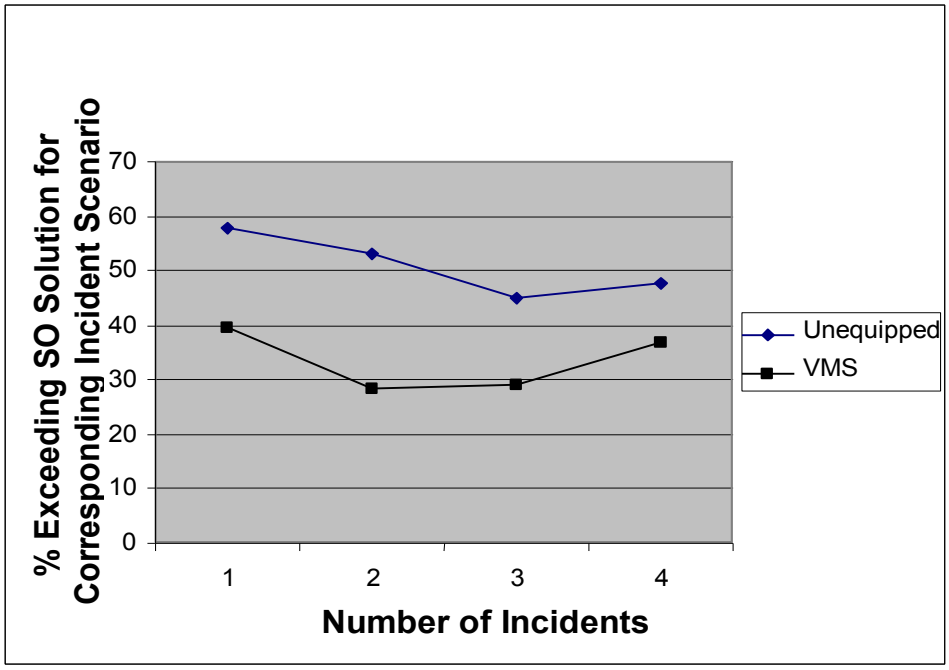

FIGURE 7 Comparison of VMS control heuristic performance across incident scenarios.

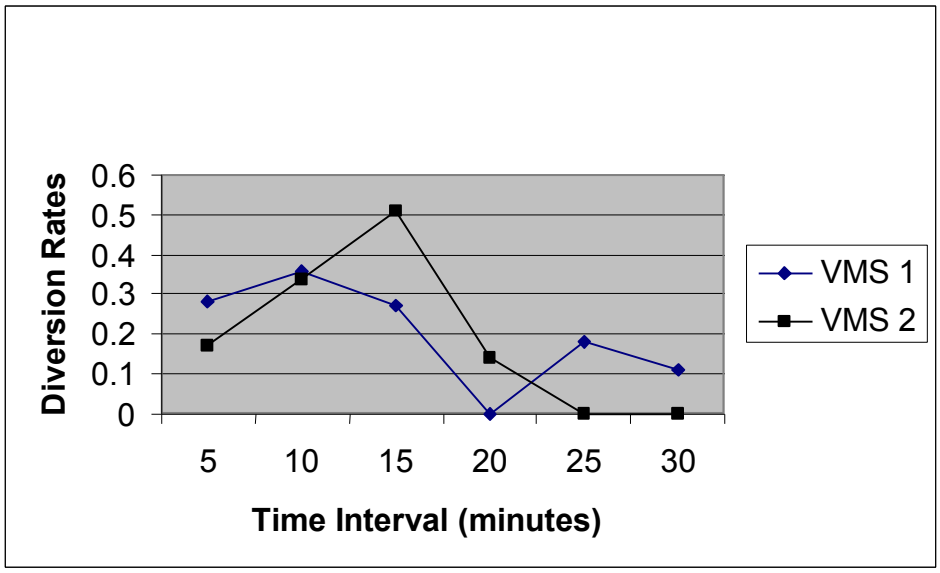

FIGURE 8 Diversion rates for VMS in two-incident scenario.

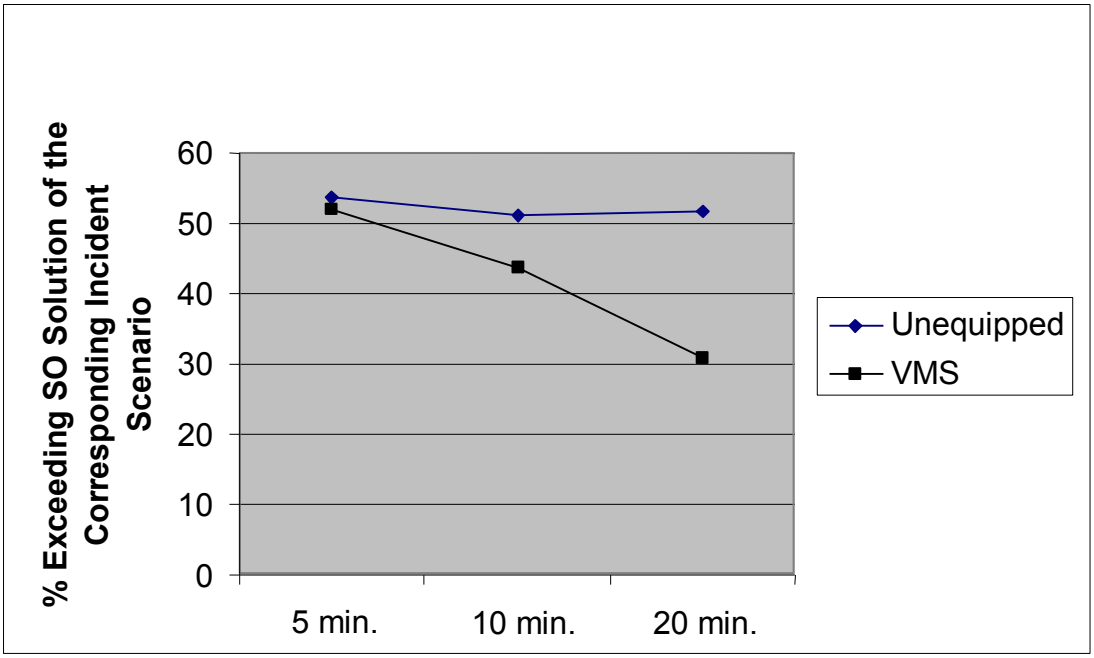

FIGURE 9 VMS control heuristic performance for varying incident durations.

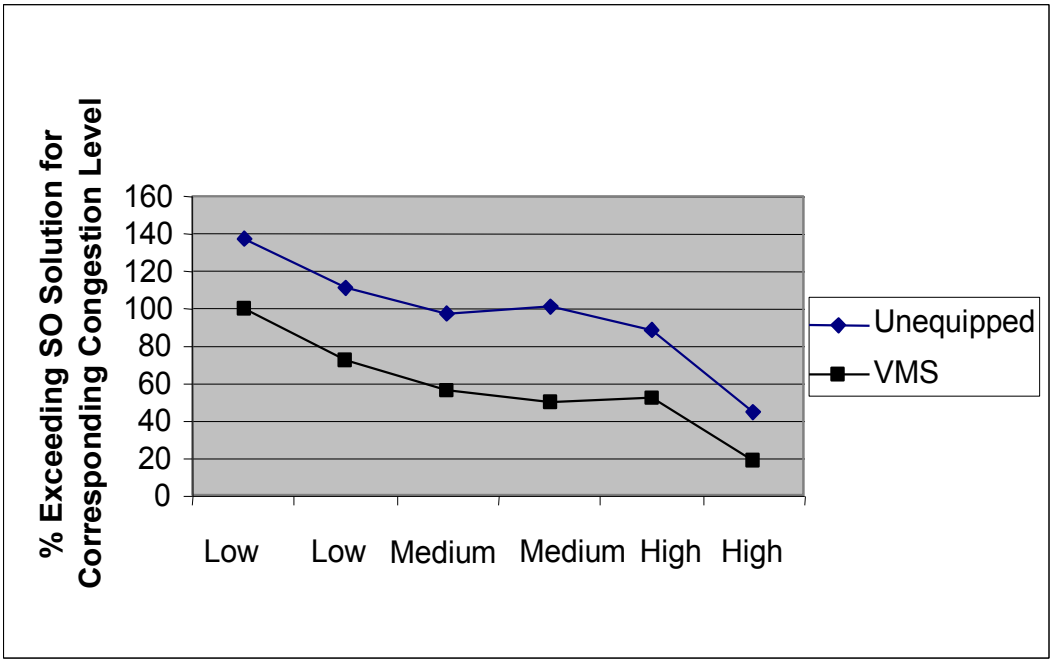

FIGURE 10 VMS control heuristic performance with varying network loading levels.

TABLE 1 Effect of VMS Message Content[a]

VMS Message Type	Message Content	Relative Willingness to Divert				
		1 %	2 %	3 %	4 %	5 %
1	Occurrence of accident only	13.7	33.9	26.6	13.3	12.5
2	Location of the accident only	20.2	33.1	22.6	11.3	12.9
3	Expected delay only	9.3	12.9	39.5	23.8	14.5
4	The best detour strategy only	7.7	18.5	30.2	25.0	18.5
5	Location of the accident and the best detour strategy	2.0	4.0	22.6	35.1	36.3
6	Location of the accident and the expected delay	0.8	0.8	19.8	38.3	40.3
7	Expected delay and the best detour strategy	2.0	2.0	13.7	33.5	48.8
8	Location of the accident, expected delay, and the best detour strategy	1.2	2.0	5.6	19.8	71.4

a Adapted from (1)