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Simulation-based Evaluation of Using Variable Speed Limit in Traffic Incidents

Siham Farrag* [a,c], Moulay Youssef El-Hansali[a], Ansar Yasar[a], Elhadi M. Shakshuki[b]

[a]*Transportation Research Institute (IMOB), Hasselt University, Hasselt, Belgium*

[b]*Jodrey School of Computer Science, Acadia University, Wolfville, Canada*

[c]*Middle East College, Muscat, Oman*

Abstract

Variable Speed Limit (VSL) systems are used to improve the traffic conditions on road by adjusting the speed limits according to current traffic situations. The variable speed limit system usually comprises of stationary detectors to estimate the traffic condition and dynamic variable message signs at predefined locations for the application of new speed limits. In connected environment, the system can recognize bottlenecks due to the incident and, further, it is possible to use direct control of the connected vehicles to adjust vehicle speeds towards the new traffic situation. In this study, we propose a variable speed limit framework based on connected vehicles environment to improve the management of non-recurrent congestion. The proposed framework is evaluated in terms of traffic efficiency, safety, and environmental impact using microscopic traffic simulation. Furthermore, economic evaluation of these strategies is performed to determine the financial feasibility of their implementation. The results indicate that the VSL system manage to improve traffic efficiency, safety and environmental impact during the incidents. However, it is found that the results depend on incident location and incident severity (number of lanes blocked, and the incident duration).

Keywords: Connected vehicle; VISSIM; Traffic congestion; ALINEA.

* Corresponding author. Tel.: +3211269138
E-mail address: siham.farrag@uhasselt.be

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1. Introduction

The limited funding available for roadway capacity expansion and growing funding gap, in conjunction with the increasing congestion and the need to ensure the efficient utilization of the existing facilities, creates a critical need for innovative Incident Management options for traffic agencies. Recently, significant emphasis has been laid on the application of advanced information and communication technologies in transportation on the basis of the Intelligent Transportation Systems (ITS) [1-2]. ITS technologies have contributed to new ways to manage and operate existing transportation infrastructures with the aim of increasing efficiency, reliability, safety and improving the environment without necessitating major physical changes in the road infrastructure [2-4].With current advancements in positioning, information and communication technologies, Connected Vehicle (CV) technologies enable infrastructure and vehicles to share information about aggregated traffic such as speeds and traffic flows and individual vehicles in real time [5-6]. Various CV technologies have been introduced such as variable speed limit (VSL), route guidance (RG), and ramp metering (RM), Car2X technology [5-6, 36] to improve traffic management for recurrent and non-recurrent congestion.

Variable Speed Limit (VSL) systems consist of a series of dynamic VSL signs and associated detectors measuring the traffic conditions. Variable Speed Limit (VSL) systems enable dynamic change of posted speed limit in response to changing traffic conditions which may be due to lane closures, reduced visibility, work zones, or any incident [5-9].

Different research studies have justified the benefits of deployment of VSL control systems in relieving freeway congestions, improving safety, and/or reduce the emission of greenhouse gases and fuel consumption under different situations [5-10].

Therefore, the aim of this study is to evaluate and quantify the effectiveness of VSL strategy in connected vehicle environment to enhance the performance of existing transportation infrastructure during incident and reduce the need of constructing new roads or adding more lanes. Furthermore, economic evaluation of this strategy is performed to determine the financial feasibility of its implementation. In this study Traffic microsimulation package VISSIM and VisVAP [14] was used to evaluate VSL Strategy.

The remainder of this paper is organized as follows: after the introduction, a summering the theoretical background of VSL control and related research studies are presented in section 2, then experimental design and data collection are discussed in section 3, followed by experimental results and discussions in section 4, and finally concluding remarks and future work are discussed in section 5.

2. Background

2.1. Variable Speed Limit (VSL) Algorithm

VSL control is to change the current speed limit according to the current traffic situation based on the observed traffic conditions close to the VSL sign [5, 11]. The choice of a suitable speed limit is decided by the VSL algorithm [5]. Generally, four different types of VSL control algorithms are commonly proposed in the literature: rule based, fuzzy-logic based, analytical and control-theory based [5,10].The design of the control algorithm of the variable speed limit system mainly depend on the purpose of the VSL system, the complexity and the level of detail of the control algorithm [5,10]. From previous literature review, it seems that the Mainline Virtual Metering (MVM) controller, which is based on fuzzy logic algorithm, produces better results regarding highway Level of Service (LOS) and exhaust emissions[2, 5,14,15]. Moreover, it was found that it is usually better to use the MVM controller when the mainline traffic volume is high. [14-15]. Therefore, our study will focus on the mainline virtual metering (MVM) algorithm. The mainline virtual metering (MVM) control approach is designed based on the concept of ramp metering [14] which reduces congestion on the motorway by limiting the on-ramp inflow. One of the most used local ramp metering algorithms is ALINEA [20]. The main idea of this control law can be represented by equations (1-4)[14].

$$R(kT_1) = R[(K-1)T_1] + K_T[O_d - O(kT_1)] \qquad (1)$$

where K is the time step, T_1 is the discretization time, $R[(K-1)T_1]$ is the ramp metering command from the previous time step, K_T is a control parameter, $O(kT_1)$ the measured downstream occupancy in the current time step, and O_d

the desired value for the downstream occupancy that is typically chosen close to the critical occupancy O_c. The ALINEA integral control strategy can be generalized to regulate the metered flow rate Q_i from highway section $(i-1)$ to i. The desired flow rate Q_i can be obtained from the following equation.

$$Q(kT_1) = \begin{cases} Q_{\max}, if \bar{Q}_i(kT_i) > Q_{\max}, \\ Q_{\min}, if \bar{Q}_i(kT_i) \le Q_{\min}, \\ \bar{Q}_i otherwise \end{cases} \tag{2}$$

The flow command has to be mapped into a speed limit command using the flow-speed relationship. The mapping $f(Q)$ is based on the estimated flow-density relationship that is assumed to be:

$$q = \rho V_f \exp\left[-\frac{1}{\alpha}\left(\frac{\rho}{\rho_c}\right)^{\alpha} \right] \tag{3}$$

where V_f is the free flow speed, ρ_c is the critical density, and α is estimated online or offline using real traffic data. The new value of desired speed limit can be determined by the function

$$\bar{V}(kT_1) = f(Q_i(kQT_i) \tag{4}$$

2.2. Simulation studies

Field operational tests to the new ITS technologies tend to be expensive, time consuming, and sometimes impracticable and prone to illegal issues [16-18]. In recent years, the microscopic approach has been given more importance in traffic operations and safety studies due to its cost effectiveness and risk-free benefits [7]. Many microscopic simulation models such as VISSIM, CORSIM, and SUMO have been widely used in evaluating ITS technologies [16-18]. VISSIM seems to be one of the main software packages in the field of transportation and it proved its effectiveness among others [19]. In recent years, simulation has emerged as an alternative tool to evaluate the performance of dynamic traffic controls, compliance rates, and to select an appropriate control design. Mohd et al. (2017) studied the impact of Variable Speed Limit (VSL) system to improve mobility on congested freeway in Istanbul using VISSIM with MATLAB to implement VSL algorithm based on volume, occupancy, and average speed. They concluded that the driver compliance to VSLs is an important factor for better results [20]. Stephen et al. (2017) performed a detailed microsimulation analysis for Active Traffic Management ATM strategies (ramp metering, variable speed limits, and hard shoulder) while commenting on their effectiveness under cases of recurring and non-recurring congestion freeway corridors. They found that all ATM strategies can improve the performance for the recurring congestion. However, for the non-recurring congestion scenario, all strategies led to a worse network performance as compared to the case without the strategy except for variable speed limits, which showed a 27.2% reduction in system delay and freeway-arterial coordinated operations [21]. Han et al. (2017) developed Model Predictive Control (MPC) approach for VSL control strategies, including VSL control strategies for mixed traffic flow, and VSL in a CAV environment using VISSIM. They concluded that MPC is effective to resolve freeway jam waves [22].

3. Developing VSL Model

In this study we will use VSL control based on the traffic breakdown prevention strategy by Hegyi (2004) [7] . We aim at mitigation shockwaves or bottleneck problem before the incident area through slowing down the traffic upstream the incident area. This in turn reduces the inflow into the incident area and thereby dissolves the congestion at the incident area. In our study, we tested various combinations of traffic incidents and response strategies in the study area during peak hours (AM and PM).

3.1. Study Area and data collection

A case study simulation was carried out for a round nineteen -kilometer segment of a multi-lane freeway, sultanate of Oman between Interchange (IC) IC 6-IC12. The segment consists of 6 sections of on/off ramps. The sections length varies between 1.8 km and 5.4 km. Each section consists of 6 lanes, 3 lanes carriage ways in each direction. The three lanes are separated by 12.0 m concrete median with landscape and light pole [23]. The average lane width is 3.65 m with inner shoulder of 2.5 m and outer shoulder of 2.0 m [25]. The posted speed limit is 120 km/h for passenger cars and 100 km/h for heavy trucks and buses [23]. The chosen section is illustrated in Fig. 1.

Fig. 1. The 6 section at Muscat Expressway.

In order to develop our micro-simulation model, different types of data were used. These data include traffic data (including *traffic volume, traffic composition, average speed, and travel time* for each direction section), geometric data (route patterns such as number of lanes, lane width, shoulder width, road classification, and road type), and incident data (e.g. number of incidents, incident type, location of incident, incident time and duration, number of blocked lanes). The geometric data and the traffic data were collected from the 'Supreme Council for Planning' and 'Muscat Municipality' respectively [24,25]. The incident data were collected from the Royal Oman Police (ROP) records. For the purpose of our study, every incident was characterized by several parameters including incident *location, number of lane closure, and incident duration.* The incident durations vary between 15 minutes and 50 minutes. Traffic data vary between 4430 vehicle/h and 7945 vehicle/h., with heavy vehicle percentage ranging between 7% and 17%. The average speed varies between 54 km/h to 101 km/h [25]. To develop the micro-simulation model, the collected data was checked and verified for allowable error (coefficient of variation (c.v) and percentage error (e) <5% at t-95) [26-27].

3.2. Building the base-model

The first step in our approach is to build the base model (network coding) where we create a scaled base model using the VISSIM interface by utilizing Google-Earth that includes the driveway and, the merge/diverge section. The model also contains the traffic data such as traffic volume at each input point, desired speed, and traffic composition data. Two separate input traffic flows were assigned to the mainline and the on-ramp, respectively. A set of static vehicle routes (VISSIM static routing is used to model the current transportation road network via routes created based on a fix sequence of links and connectors) [12,27] were defined on the mainline as well as a route for run-through traffic in merging and diverging area. The model is also calibrated and validated to ensure that the base is representing the real case conditions by using total number of flow and average speed for calibration process and travel time for validation process. The Geoffrey E. Havers (GEH) statistical procedure was used to evaluate the calibration results [26]. GEH values in the range of 0-5 convey that the simulated volume is closely correlated to the observed traffic volume, while those in the range of 5-10 convey that there is a good match between the modelled and observed traffic volume. In our study All the road links show a GEH less than 5. Three statically analysis (Goodness-of-fit Measurement) were done to validate the calibrated model, namely, The Root Mean Square Error (RMSE), the Mean Absolute Normalized Error (MANE), and A Coefficient of Correlation (CC). All Goodness-of-fit Measurement were within an acceptable range (less than 15%) [26-27]. To minimize the impact of the stochastic nature of the VISSIM, our simulations models were run 10 times [34,35] for 4500 to 5400 seconds including warm-up and cooling-down periods which vary between 600-900 seconds.

3.3. Incident simulation

In our study the incident was simulated as a parking lot that allows the disabled vehicles or the vehicles involved in an accident to stay in the blocked lane/lanes as a parking lot during incident time, and allows other vehicles to use the opened lane/lanes [12]. To achieve that, the route is active only during the incident time and partial route is used to direct all traffic over created connector during the incident through setting the time interval for the partial route during the time of each incident [12].

3.4. Modelling Technique

3.4.1. VISSIM COM Interface

The most common way to estimate the traffic state is by the use of data from stationary detectors, such as loop and radar detectors [2,15]. In VISSIM, detectors are modelled as network objects on links [14]. In our study, one detector was defined per lane per vehicle class lightweight vehicles (Car, Mini Bus (< 16 Seats), LGV (Light Goods) while and heavy vehicles (Medium Goods Vehicles (2 - Axle Truck) , Buses, HGV). Since loop detectors cannot directly communicate with the routing decision, one signal controller was added to receive detector variables, interpret control logics, and create signal commands on a discrete time step [14,36] as the bases of vehicle to infrastructure in Connected Vehicle (CV) environment [5]. In our study, Traffic actuated signal controls was simulated by the external signal state generator add-on module VAP (Vehicle Actuated Programming) between 500–700 m beginning of the incident [9,28]. The signal settings used for VSLs are indicated in Fig. 2.

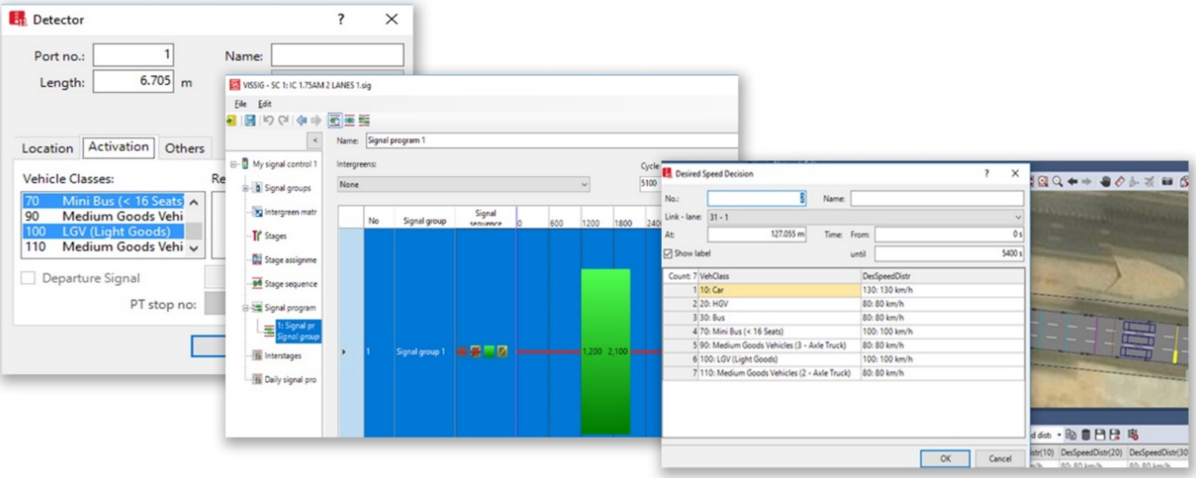

Fig. 2. Settings used for VSL Strategy .

3.4.2. VSL control algorithms Technique.

Using VisVAP, the current flow data is evaluated using the detector values. The smoothened flow data is then checked against the relevant threshold values of the various speed limits. If necessary, a new speed limit is selected by assigning a different speed distribution to the desired speed decisions in VISSIM. Firstly, the MVM generates command signals after equally spaced time intervals. the parameters ‘Q_{max}’, ‘Q_{min} , maximum speed limit value ($_{max}$) and minimum speed limit value ( ) were calculated using the equation in section 2 [14]. The flow chart shown in Fig. (3) summarizes the process involved.

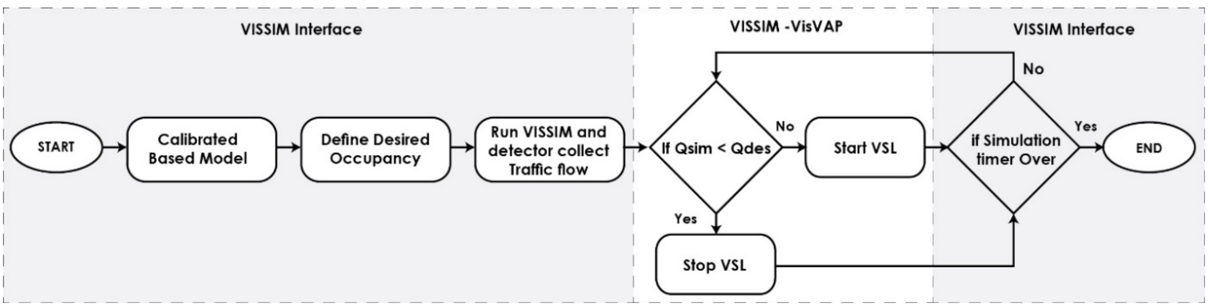

Fig. 3. Simulation Framework for VSL Strategy.

4. Results Analysis and Discussion

In this section, the VSL Control strategy is evaluated in comparison with the case of no VSL based on their impact during the incident. To evaluate the effectiveness of VSL as TIM strategy in term of mobility and safety, different Measures of Effectiveness (MoEs) were chosen that include *total travel time* (is the sum of the travel time of vehicles traveling within the link or that have already left the Link.), *bottleneck throughput* (capacity), *average delay* and *number of stops*(which represents the stop-and-go shockwaves in the network, reducing this number intend to reduce the secondary accidents[35]), *stopped delay* (which is the time a vehicle is stopped in queue while waiting to pass through the bottleneck area). In terms of sustainable and energy-efficient transport system options, fuel consumption and air pollution relevant emission created by different models are another important performance measure. Therefore, vehicle emission regarding carbon dioxide (CO2), nitrogen oxides (NOX) and Volatile Organic Compounds (VOCs) and fuel consumption were measured [26-27]. Reducing the value of this measure of effectiveness reflects a significant increase in efficiency of traffic flow and safety along the road [29-30]. Finally, in order to evaluate the feasibility implementation of our strategy in context of economic evaluation, Benefit-cost ratio (B/C) and net present value (NPV) methods were used [31].

4.1. Performance, Safety and environmental Impact

In general, and regarding to the links, the proposed VSL strategy can increase bottleneck throughput by 0.7% and 22.5% compared to the No-VSL scenario. The total increase in throughput during AM and PM was 7.8% and 11% respectively. The vehicle travel time and vehicle delay have reduced 3% to 90% and 3% to 60% respectively. Moreover, all emissions and fuel consumption were decreased 3.5% to 87%. Finally, the total number of stop delays and average stops were reduced during AM by 14.4% and 10% respectively and 0.2% and 16.6% respectively. Table 1 gives a summary of the results for the two scenarios (with VSL and without VSL) during AM and PM peak hours.

Table 1. Summary of the results for the two scenarios.

	LINK	Incident Duration	No of lane blocked	With VSL Control					Without VSL Control				
				VEHS (veh/h)	TRAV TM (sec)	VEHD ELAY (sec)	STOP DELAY (sec)	STOPS (number)	VEHS (veh/h)	TRAV TM (sec)	VEHD ELAY (sec)	STOP DELAY (sec)	STOPS (number)
AM	Link1	30	2	5216	578.98	493.12	10.25	31.83	5433	437.85	340.33	9.91	28.12
		30	2	5158	572.6	481.63	11.68	33.04	5922	436.77	334.94	9	27.78
	Link2	20	1	5528	458.27	324.16	4	6.85	6460	340.65	200.86	2.98	4.49
	Link3	35	2	4071	765.3	598.16	25.32	71.32	4100	743.63	578.29	24.7	71.38
	Link4	25	2	4333	1250.22	917.68	19.51	49.75	5075	874.01	572.17	15.44	47.14
	Link5	15	2	5025	281.06	220.66	15.36	26.78	5360	250.62	181.01	11.28	20.83
		15	1	5707	210.8	150.12	4.4	7.8	6015	171.38	107.98	3.46	6.11
	Link6	25	2	4259	438.02	278.89	3.17	8.67	4349	315.99	140.8	2.8	7.4
		25	2	4385	396.33	234.83	4.69	6.86	4386	291.45	114.41	4.65	5.31
	Total			43682	4951.58	3699.25	98.38	242.9	47100	3862.353	2570.8	84.22	218.56
PM	Link1	50	3	2286	1527.31	1313.84	1083.52	13.2	2655	1331.05	1292.99	1087.28	12.63
	Link2	25	1	4229	270.67	152.75	1.21	1.99	5180	237.77	95.3	1.02	1.49
	Link3	25	1	4994	307.26	167.8	1.19	2.24	5002	239.31333	97	1	1.6
	Link4	25	2	3901	686.92	351.98	11.64	22.69	4238	591.52	232.41	8.84	20.25
	Link5	15	2	4078	144.36	82.36	2.97	2.99	4411	99.17	33.75	1.76	1.19
	Link6	15	2	3545	750.99	592.57	13.76	35.55	4082	625.41143	464.5	12.5	30.78
	Total			23033	3687.51	2661.3	1114.29	78.66	25568	3124.2347	2215.9	1112.4	67.94

To calculate the exhaust emission of vehicles in VISSIM, Simplified method via node evaluation was used [14]. This method is based on standard formulas for consumption values of vehicles from TRANSYT 7-F, a program for optimizing signal times, as well as data on emissions of the Oak Ridge National Laboratory of the U.S Department of energy [14]. The data refers to a typical North American vehicle fleet and does not differentiate between individual vehicle types. This allows a simpler comparison of the emissions produced during different scenarios

[14]. Fig 4 shows the results of fuel consumption and emissions, namely Carbon Monoxide (CO), Nitrogen Oxides (NOx), and Volatile Organic Compounds (VOC) produced by different scenarios. The results show that the proposed model is able to reduce fuel consumption and emissions by percentage varies between 3.5% and 46.5%, compared to No-VSL.

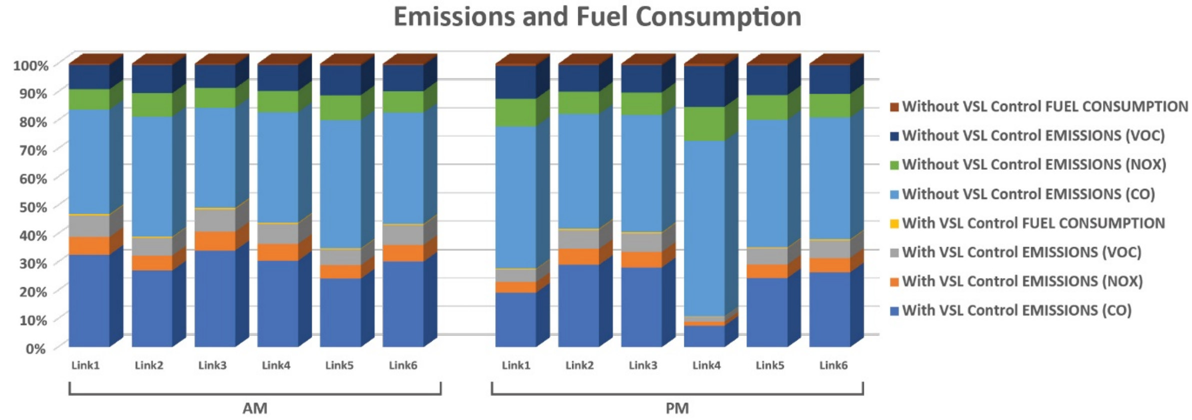

Fig. 4. Results of fuel consumption and emissions.

4.2. Economic Evaluation

The annual benefits and costs associated with implementation of VSL strategy are listed in table 3. Total benefits (B) are calculated as the sum of Vehicle Operating Cost (VOC), emissions, and travel time savings. Similarly, total costs are determined as the sum of total initial fixed costs and the annual operation and maintenance costs. Benefit-cost ratio (B/C) and net present worth (NPW) are estimated using a discount rate equal to 5%- and 10-year analysis period [31-32]. Vehicle emissions, in general, are influenced by vehicle age, mileage, size, engine power and VMT (vehicle miles travelled) [33]. However, in this study, it is assumed that the vehicle type is the only factor influencing the vehicular emission rates. The unit cost (€/ton) of pollutants were estimated as CO (106.5 €/ton), VOC (563.09 €/ton), and NOx (10,052.22 €/ton) [32-33]. Using these values, the emission saving for all the links during AM and PM were found 35.5 € (39.7$) for CO emission, 982.4 € (1097.2$) and for NOX emission, and 65.5 € (73.2 $) for VOC emission.

To estimate travel time savings during the morning and afternoon peak duration, it has been assumed that the trip purpose for all the automobiles is work related trip. The corresponding value of travel time (VOT) for a single occupant vehicle (SOV) is assumed to be $30/hour, while the VOT for automobiles with higher occupancy is equal to occupancy multiplied by $30/hour and for Heavy vehicles is in range of 100 $/h [34,37]. Based on these assumptions the total travel time saving in our study was 121.5 $ saving for work trips and 220$ for Heavy vehicle trips during PM and AM peak hours. A similar segment wise analysis is performed to estimate the Vehicle operating cost (VOC) savings. The VOC savings are determined by estimating the fuel cost savings using the AASHTO model as described in [32-33]. The VOC saving is calculated as presented in the following equation while assuming that the fuel cost is 3.5$ per gallon [34].

VOC savings = The average travel time savings x the fuel cost per gallon x the corresponding fuel consumption values [33] (5)

The total annual average VOC saving is determined by summing the VOC savings for all the vehicle types and it found to be 60353 $. The expected costs associated with the implementation of VSL are depicted in table 2.

Table 2: Costs Associated with Implementing VSL [33]

Component	Unit Cost	Quantity	Total Cost ($)
installation cost	50,000	1	50,000
Communication from detectors to meters (twisted pair wire)	100,000	1	100,000
Detector cost	2,800	1	2800
Series processor	8,000	1	8000
Total fixed installation costs			160,800
Annual operating and maintenance costs	10% of installation costs		16,080

Based on the above economic evaluation for 10-year analysis period, the NPW value was found to be positive and equal to $3,273,341, while the B/C ratio is 1.90. This indicates the implementation of VSL is economically viable.

Table 3: Annual costs and benefits of implementation of VSL

VOC Savings ($)	Emission Savings ($)	Travel Time Savings ($)	Total Benefits ($)	Annual operating & maintenance Cost ($)	Initial Fixed Cost ($)	NPW
60353	1210.1	341.5	61904.6	16,080	160,800	193,045 $
Benefit Cost Ratio						2.2

4. Conclusions

We conclude that VSL strategy provides cost effective option in traffic incident management to improve the traffic efficiency, safety, and mobility, and provide an environmentally friendly approach.

Generally, the improvement in all the MOEs was more significant during PM peak hours than AM Peak hours and where the traffic volume was high.

Moreover, the efficiency of this strategy depends on other factors such as incident location and incident severity (number of lanes blocked, and the incident duration). Considering the incident severity, we observed that the effectiveness of VSL strategy was higher in case of high severity in term of improving the highway mobility. For example, in the case of the link 2 during AM Peak hours , the incident duration was 20 minutes with 1 lane blocked the improvements when using VSL in the MOE throughputs and travel time were 16.8, 25.7 %, respectively while for link 4 where the incident duration was 25 minutes and the number of lanes blocked were 2, the improvement in mobility was 17.1% and 30.1% for throughputs and travel time respectively. Considering the location of incident, we found that VSL strategy gives better results in in terms of mobility (total increase in throughput, travel time) when the incident occurs near to diverging area compared to the same incident occurring at merging area, while it showed better improvement in terms of safety ((number of stops) and environmental impact (all emissions and fuel consumption) when incident occurs near merging area. For example, at link 6 AM, simulations results showed the improvement in throughput and travel time at diverging area were 2.1% and 27.9% respectively while the results were 0.2% and 26. % respectively at merging area. However, the improvement in safety and environmental impact were 22.6 % and 23.6 % respectively at merging area and 23.02% and 14.65% respectively at diverging area.

Finally, the future work we plan to evaluate different strategies and their combination while comparing them in addition to provide the most effective strategy in different situations.

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