A Framework to Evaluate the Impact of Variable Speed Limit Systems on Work Zone Traffic Operation Using VISSIM

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Prepared by

Abhro Mitra
DKS Associates

1400 SW Fifth Ave, Suite 500
Portland, OR 97201
Ph: (503) 243-3500 Ext: 249
Fax: (503) 243-1934
E-mail: axm@dksassociates.com

Prahlad D. Pant, Ph.D., P.E.
President, PDP Associates Inc.

270 Northland Blvd, Suite 319
Cincinnati, OH 45246
Ph: (513) 772-0747
Fax: (513) 772-2184
E-mail: Pant@PDPassociates.com

ABSTRACT
In this paper, we present an analytical framework that can be adopted to analyze and measure the impact of Variable Speed Limit (VSL) systems on traffic operation. A freeway work zone is taken as a case study where typically variable speed limit systems are deployed. In the first stage, the existing traffic conditions are modeled using micro-simulation tool VISSIM. The calibrated base model has been statistically validated within 95% confidence interval. The next stage is to perform several sets of simulations and deploy various speed reduction strategies under different operational scenarios. The simulation results are quantified in terms of several measures of effectiveness (MOE) under three scenarios 1) Base scenario 2) Speed limit variation 3) Speed limit variations along with changes in lane widths. In the final stage a multiple regression analysis is carried out to develop a mathematical model. An equation is developed that represents speed as a function of network delay and lane width. With this equation an optimal speed limit can be determined for a specific roadway width without running extensive computer simulations. Although this equation is case specific, the methodology is generic and can be applied to other situations as well. This paper suggests a step by step procedure involving in-house laboratory simulations that could help traffic engineers to recommend an optimal speed limit that would have minimal impact on traffic operations.

1 INTRODUCTION

Setting up work zones on the freeway to facilitate construction is a regular feature that affects traffic operation. Reduced speed limits and lane closures lead to traffic congestion causing significant delays. Various measures are taken to pre-warn the commuter of the construction activity. Advance Travel Information System (ATIS) technologies like Highway Advisory Radio, Internet Kiosks, Changeable Message Signs etc are deployed to alert the commuters. In addition, lower speed limits are assigned on these work zones to ensure safety.

The work zone speed limit typically remains fixed under varying traffic conditions. Hence, there has been much recent interest in studying the performance of Variable speed limit systems that adapt according to the traffic conditions on the roadway, thereby improving traffic flow. It would be cost effective for transportation agencies to pre-conceive the impact of deploying these systems before hand. This paper provides with a framework to analyze and quantify the impact of such systems by in-house laboratory simulations.

Computer simulation modeling has evolved as a powerful and effective tool to visualize and analyze traffic conditions even evaluate strategies, without impacting traffic on actual site. In this study, a micro-simulation tool VISSIM is used to model the traffic on a freeway work zone. This is a stochastic, microscopic time step and behavior based simulation model that was developed by Dr. R. Wiedemann from University of Karlsruhe in Germany. The model follows the principles of car following and lane changing logic [10].

The study area is a work zone on a trumpet interchange on the I-10/I-110 freeway located in Escambia-county in north-western Florida. This $76 million project involving the six-laning of the I-10 (from east of Old Palafox Highway to east of Davis Highway) and six-laning of I-110 (from the I-10 interchange south to Airport Boulevard), is scheduled to be completed by the year 2006. The subsequent sections of this paper outline the methodology used to evaluate the VSL system and analyze the impact on traffic operation before an actual on site deployment.

2 MODELING PROCEDURE

The modeling process involves setting up a base network in VISSIM to run test simulations under various scenarios. Various parameters are coded into the simulator and test runs are performed to emulate the actual site conditions. A methodical and thoughtful modeling process ensures a close to real representation and greater accuracy of the simulated results. A detailed, step by step description of the methodology and approach adopted in this study are presented in the following sections.

2.1 Coding the Base-Network

The base network is constructed using links and connectors that represent the test bed (refer Figure 1). Various traffic parameters like traffic volume, traffic composition, acceleration and deceleration values, vehicles type, grade separation and lane widths etc. are coded into these links. Table 1 shows the directional movement of each link identified by its unique ID corresponding to the network.

Figure 1 – Interchange Network

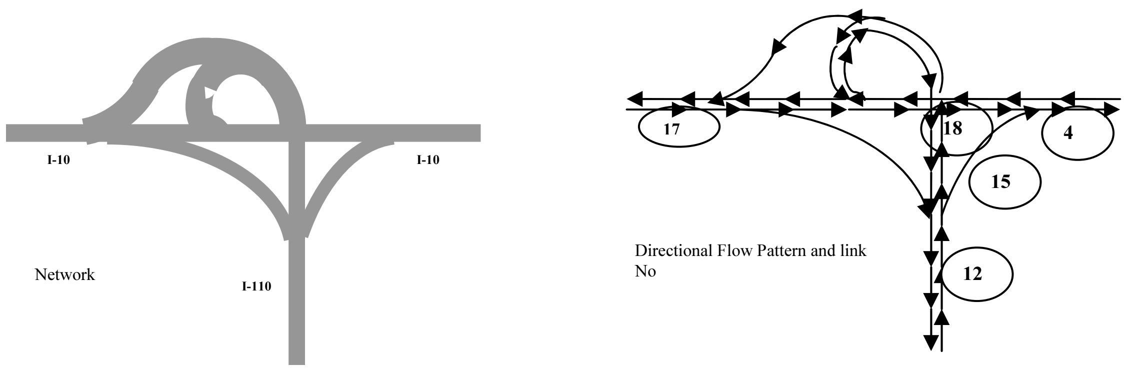


Table 1 - Directional movement of each link (ID) in the model

Link ID in network	Direction on the test bed
1	I-10 (from west to 1)
2	I-10 (from west, 1 to 3)
3	I-10 (from west, 3 to east)
4	I-10 (from east to 2)
5	I-10 (from east, 2 to 1)
6	I-10 (from east, 1 to east)
7	I-110 (from south to 4)
8	I-110 (from south, 4 to 1)
9	I-110 (from north 2 to 4)
10	I-110 (from north, 4 to south)
11	Ramp (1 to 4)
12	Ramp (4 to 3)

As there are six possible movement patterns on the network, six routing decisions are implemented. Table 2 depicts the code ID’s used in the model for the six corresponding directions (also refer figure 1 to observe the directional movement).

Table 2 - Routing code and direction

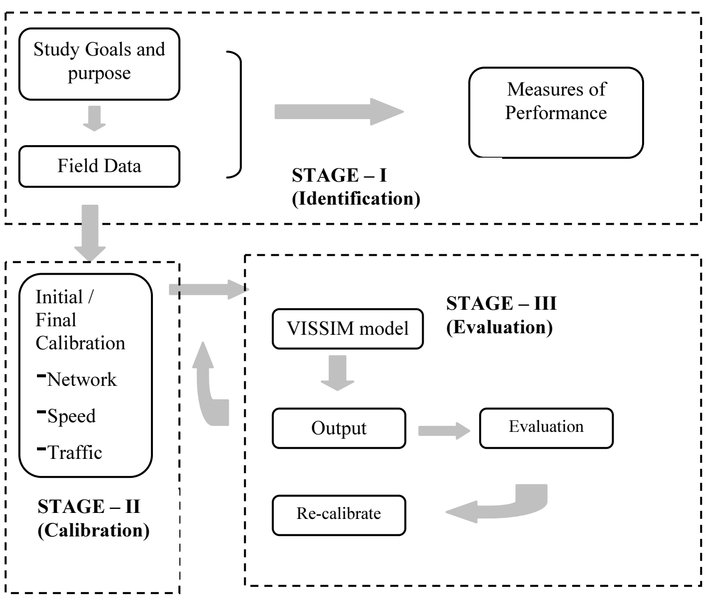
Code ID.	Routing direction
2-1	I-10 east to west
2-2	I-10 east to I-110 south
9-1	I-10 west to east
9-2	I-10 west to I-110 south
10-1	I-110 south to I-10 west
10-2	I-110 south to I-10 east

After modeling the base network with traffic operation parameters, the next step is to model the simulation control parameters. This involves specifying the simulation time, time interval, and the simulation speed. Random seeds are used in the simulation run time parameters to emulate a heterogeneous traffic pattern. Default values in the model are used for 'driver behavior parameters'.

2.2 Calibrating the Model

Model calibration as defined by Hellinga [9] is a process by which the user of a model adjusts various parameters of the model to obtain results that closely reflect the ground parameters. Figure 2 shows highlights the various steps that are involved in calibrating the model.

Figure 2 Methodology for Model Calibration



The first stage in model calibration is identification of the various parameters that need to be adjusted. It is important at this stage to have an idea of the measures of effectiveness (MOE's) that are desired from the simulation. A lot of time can be saved by tuning only the relevant parameters that affect the results. The second step is a cyclic process where we examine the calibrated model for errors and use this feedback to re-calibrate. This process is repeated until necessary to ensure that the model is a close representation of the ground reality. The final step is to evaluate the calibrated model in terms of the MOE's obtained and to ensure that the simulation is fully operative without any errors.

Initial Calibration

Various parameters like speed, vehicle types, routing etc are modified to the actual test bed conditions at this stage. Speed for the cars and HGV vehicles are coded separately in the network on all links. A range of speed for cars between 55-70 mph and a range for the HGV between 50-55 mph are used (to start with) identified by code-ID's 90 and 85 respectively. Some other parameters related to vehicle types, traffic type, size of the vehicles, emission factors etc. are also adjusted accordingly.

Re-Calibration & Error Rectification

After the initial calibration, a test simulation is executed and two errors 'simulation error' and 'merge & diverge' error are displayed. The message in the file reads "…total vehicle output in one of the links is less than the input". Since there is no error in the data input, this error is a result of unbalanced network input. Further investigation reveals that the specified simulation time was not enough for the network to load up with the actual number of vehicles. This resulted in an unbalanced network. To find an appropriate value of the random seed, a number of iterative runs are conducted and studied with different random seed values. A value that is sufficient enough for the base network simulation to load up and have a balanced input-output is finally selected. It is found that the closest pre-run time of 540 simulation seconds is needed to load the base network. This means that after 540 simulation seconds the network reaches the point when the total input of the vehicles into the network is equal to the total output from the network and it was fully loaded. The "*.npe" (network performance evaluation) file that is one of the outputs of the model is studied to factor the ratio of the actual peak hour volume in deriving the pre-run simulation time.

Merge and diverge error on the ramps

The second simulation error was due to faulty merge and diverge modeling at the on & off ramps. The entire network was clogged with traffic because the traffic on the 'on ramp' and 'off ramp' of I-10 could not merge with the mainline traffic. This error is rectified by making the merges and diverges on these ramps more precise and accurate. VISSIM is very highly sensitive to the merging and diverging of traffic because the model is based on the psycho-physical driver behavior logic. To solve this problem, the following points were taken into consideration:

- The merge section (weaving section) should be one link with the number of lanes equal to the number of lanes on the main freeway plus the number of lanes merging onto the freeway.
- There should be only one connector after the merge link (weaving section) to the main freeway. For graphical reasons an additional dummy link (not a connector) can be added at the end of the merging lane(s) to smoothen the lane reduction.
- The routes of the merging traffic must also extend past the merge link (weaving section). If not, vehicles on the merge link will not know that they need to change lanes in order to get on to the main link prior to the end of the merging lane(s).

2.3 Model Validation - Test of Confidence

Model validation is a critical step that ensures the accuracy of the calibration. A statistical test of confidence is carried out with the volume figures obtained from dry simulations of the calibrated model to the actual volume numbers. A total of 16 test simulations are completed and the data is aggregated. Mean & standard deviation are computed with the simulated and actual numbers for three legs on the network; east (on I-10), west (on I-10) and the south (on I-110). Confidence is tested for an alpha value of 1.96 with 95% interval. The equation being used is:

$$\overline{X} \pm 1.96\left(\frac{\sigma}{\sqrt{\eta}}\right)$$

where $\overline{X}$ = mean

1.96 is the α value for a confidence of 95%
σ = standard deviation

Figure 3. Graph showing confidence interval between simulated and actual volume

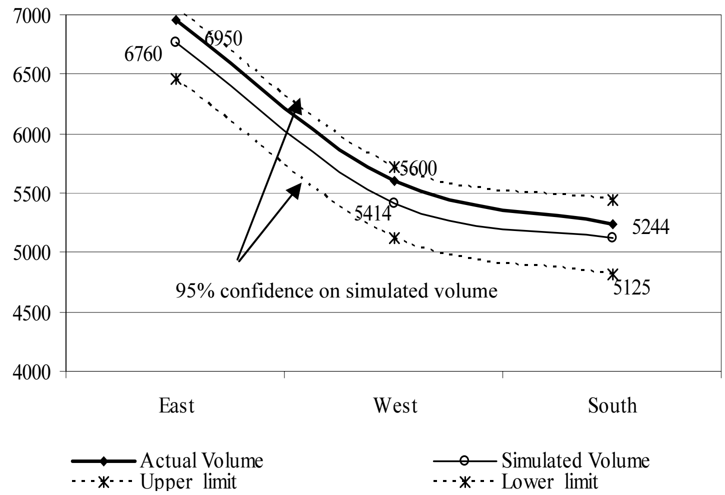


Figure 3 shows that the simulated volume is found to be within 95% of the confidence of the actual volume. As it can be seen in the figure, the simulated peak hour volume on the east leg is 6760 compared to the actual volume of 6950; for the west leg it is 5414 compared to 5600 actual volume and for the south leg the simulated volume is 5125 as compared to an actual volume of 5244.

3 ANALYSIS AND DISCUSSION

The primary objective of this project is to study the effect of variable speed limit systems. The section selected for this work-zone speed analysis is between the off ramp on I-10 (E-W) and the on ramp on I-10 (E-W). This is represented by link no. 18 in the model [refer figure 1]. Various MOE's are recorded at 60 simulation second intervals for a total simulation time of 3600 simulation seconds. The following three scenarios were taken into consideration:

- Scenario – I: Base scenario
- Scenario – II: Reduce Speed on link no. 18
- Scenario – III: Reduced speed with lane width variation on link no. 18

Scenario-I is modeled by no intervention; Scenario – II involves a speed reduction in the range of 50–55mph on link no. 18 (the work-zone) and Scenario – III incorporates lane width variation along with speed reduction. Table 3 shows MOE's for the three scenarios.

As it can be seen from Table 3, for the base scenario it is observed that link no. 12 has the highest speed with 59.54 mph and link no. 18 has the lowest speed with a value of 50.69mph. The lost time and vehicle density is highest for link no. 4. The average speed on link 18 is recorded to be 43.96mph which is much lower than the other sections. The density of traffic and lost time is also the highest with a value of 44.08veh/mile and a lost time of 0.15 sec per vehicle respectively. For scenario I & II the highest density and lost time is seen for link 4 but in scenario – III it is for link no. 18.

Table 3 Results of the three Scenarios

	Link	Speed(mph)	Density (veh/mile)	Lost time (sec)
Scenario I	4	55.168039	46.89627451	0.05254902
	12	59.548627	17.74117647	0.006470588
	17	57.563725	25.84117647	0.020196078
	18	**50.69176**	**37.36451**	**0.0266667**
	15	58.151961	10.74039216	0.025098039
Scenario II	4	55.167647	46.89647059	0.05254902
	12	59.421176	18.37921569	0.007843137
	17	57.436275	26.47921569	0.021568627
	18	**50.56412**	**38.002549**	**0.0280392**
	15	58.094902	11.39078431	0.025294118
Scenario III	4	55.75549	45.95117647	0.044117647
	12	59.452353	18.34627451	0.00745098
	17	57.494118	26.43215686	0.020196078
	18	**43.96196**	**44.089804**	**0.1564706**
	15	58.20451	11.34607843	0.024509804

Looking at these three scenarios it can be concluded that there is not much of a change in the values for scenario I & II but a significant change is observed in scenario III when a reduced speed is implemented along with a variation in lane width. It can be observed from the results that when speed is reduced on link no. 18, the work-zone affected the network drastically. The following discussion will highlight the variations observed in various parameters for this specific link.

3.1 Effect on link no. 18 – The work zone

Figure 4 shows the significant effect on speed in Scenario III. The fluctuation in the speed is very significant throughout the simulation period. It varies from as low as 30mph to 48mph with an average value of 43.96 mph. However, as seen the change in speed is very gradual for the other two scenarios.

Figure 4. A comparison of the effect on speed on link 18 for Scenario I, II and III

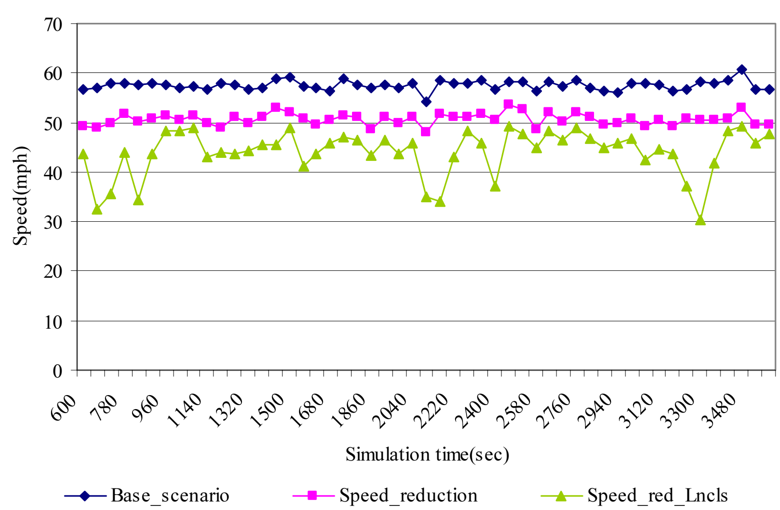
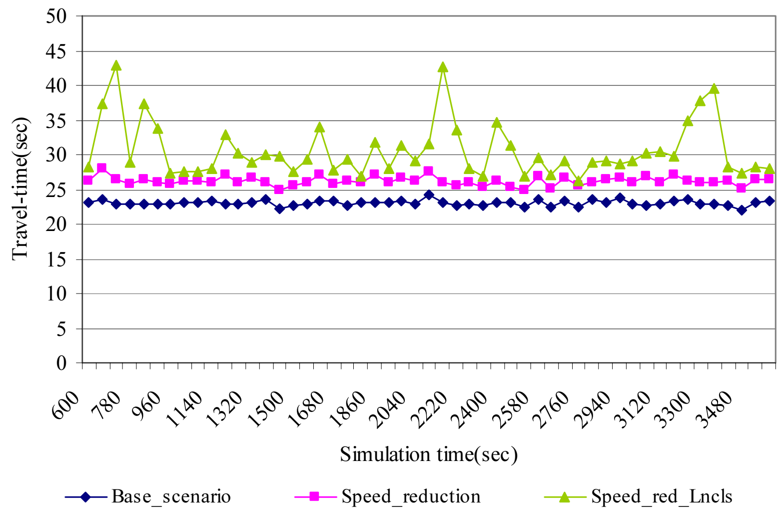


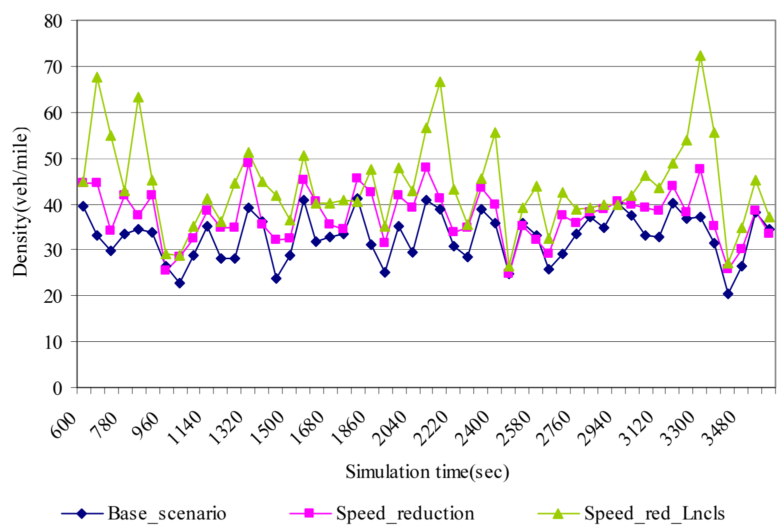
Figure 5. A comparison of the effect on Travel Time on link 18 for Scenario I, II and III



From Figure 5 it can be seen that the travel time on the link varies from as high as 45 sec to 30 seconds. Since the travel time is a function of the speed it can be seen that for lower speed values the travel time is very high and vice versa. Again it is seen that such a drastic variation is observed only for scenario III and not for scenario's I and II.

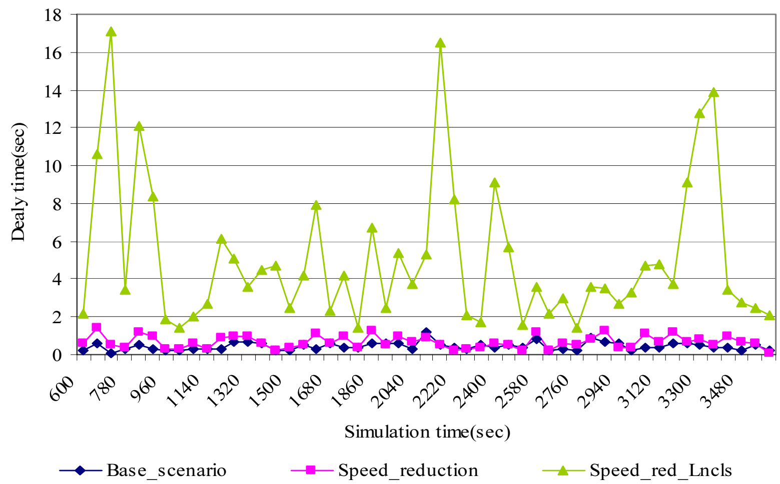
The density (vehicle/mile) graph shown below indicates heavy fluctuation for the whole simulation period. However it is to be noted that the variation for the third scenario is clearly greater than the other two as can be seen from Figure 6. For Scenario III the value of density varies from as low as 27 veh/mile to 72 veh/mile.

Figure 6. A comparison of the effect on Density on link 18 for Scenario I, II and III



As it can be seen in Figure 7 the effect on delay varies from as high as 17 sec to 2 sec. It can be concluded that there is a significant impact on delay of traffic on the work zone. This means that if during the construction activity, a lane is fully or partially closed for the traffic and simultaneously the speed is also reduced, then there could be a significant impact on the traffic flow.

Figure 7. A comparison of the effect on Delay for Link 18 for Scenario I, II and III



The above analysis clearly reveals a significant impact on the link no.18 (the work-zone) when it is subjected to speed reductions with capacity constraints. It will be beneficial to determine the optimal speed on this link that would not cause a significant impact on traffic and will ensure a free flow with lesser delay.

4 QUANTITATIVE ANALYSIS

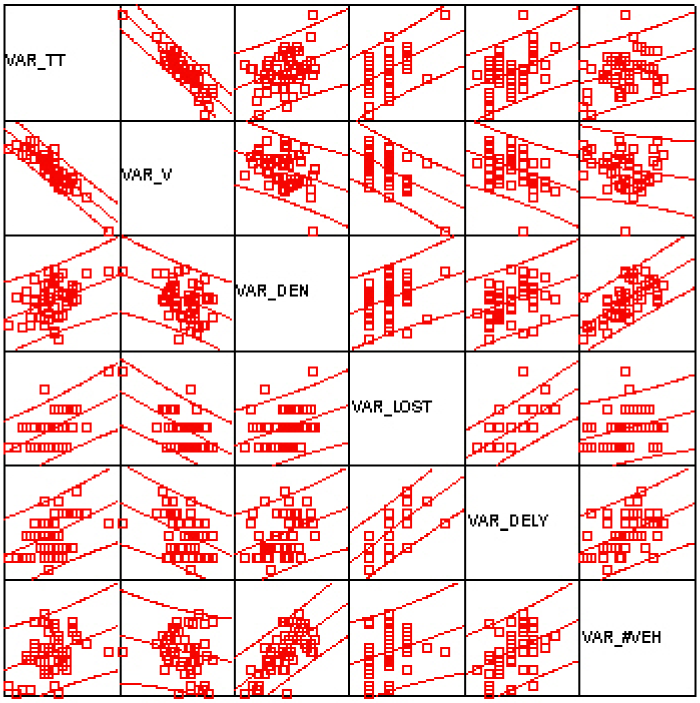
The sensitivity of the link 18 is modeled using multiple regression analysis. Developing this model would be helpful to study any type of speed variation on the work zone and study the impact on traffic operation. Simplistically a multiple regression equation can be expressed as:

$Y = aX_1 + bX_2 + cX_3 \ldots\ldots\ldots + dX_N + C$
where a, b, d…..C are constants
Y = dependent variable
X_1 , X_2 , X_3 …….X_N are independent variables

Under ideal conditions a highly sensitive multiple regression model should have a very strong correlation with each of the independent variables. The independent variables have very little correlation with each other. The regression model for this study aims at developing a relationship of speed with other controllable variables on link no. 18.

The first step is to analyze the scatter plot matrix of all the possible variables like speed, flow, delay, density, lost time and lane width (refer figure 8). A significant linear relationship is observed between some variables and for some it was a discrete plot. More linear the relation is, stronger the variables are related and better is their sensitivity.

Figure 8 Scatter Plot of the variables



After observing the relationships amongst the variables it was deduced that the controllable parameters were speed, lane width and delay. The relationship among these three variables was the strongest. It is found that the relation between speed and the delay is highly linear; and the relation between lane width and delay is also highly linear. So the skeletal equation is derived as:

$$f\{delay\} \propto f\{speed\} + f\{lanewidth\}$$

The skeletal equation shows that the dependent variable is delay and the independent variables are speed and lane-width. To justify the equation further the inter-factor correlation is computed as shown in table 4. It can be seen that the co-relation between speed and lane width is -0.01 which is very low. The correlation between delay and speed, delay and lane-width are -0.22 and -0.46 respectively, which is on the higher side and hence delay is the dependent variable.

Table 4 Inter Factor Co-relation

Variable	VAR_DELY	VAR_SPD	VAR_LNWD
DELY	1.00	-0.22	-0.46
SPD	-0.22	1.00	-0.01
LNWD	-0.46	-0.01	1.00

Table 5 shows that 't' values for speed and lane-width are -0.9201 and -1.9331 respectively, which is quite high for lane width but not so high for speed. The 't' value evaluates the significance and the accuracy of the coefficients in the model. Also it should be noted that the basic idea is to formulate a relation between speed, lane-width and delay, which is a constraint in the model. The standard error of estimate is 0.1045 which is fairly good for this model and hence the equation obtained is fairly accurate for this situation. Further analysis might be done taking more than two independent variables that might make the model more accurate.

Table 5 Variable Coefficients and Significance Level

	Un standardized Coefficients B value	T value
(Constant)	0.9772	3.4052
SPD	-0.0032	-0.9201
LNWD	-0.0452	-1.9331

The final equation derived was:

Delay = -0.0032*(speed) – 0.0452*(lane-width) + 0.9772

This equation will help in evaluating the delay on the link with varying speed limits and lane widths without running the simulation model repetitively. Also this mathematical model can be used to find the optimal work-zone speed limit that can be posted on the site under specific operational conditions. It should be realized that this equation is good for this specific case only and separate models need to be generated and similar steps need to be followed for any other study area. Depending on the site conditions, the number and type of variables will change in the equation. Typically on a work-zone the lane width has to be changed depending on the construction and this mathematical model helps to minimize the delay for a specific speed range that could be posted. The model helps to satisfy the dynamic nature of speed postings on work-zone depending on the construction intensity.

5 CONCLUSIONS AND FUTURE WORK

This paper examined the impact of variable speed limit systems under different traffic operating scenarios on a work zone using the micro-simulation model VISSIM. A test bed is modeled using static network modeling and is calibrated for site conditions. Statistical test of confidence showed that the simulated conditions as predicted by the model are within 95% confidence interval of the actual site conditions. A mathematical model has been developed that is a function of speed, delay and lane width.

Posting an optimal speed that would minimize delays in work zones is a challenge for Traffic Engineers and this research method suggests one way to tackle this situation. The mathematical equation eliminates the repeated use of the simulation tool to find an optimal speed limit and analyze the impact. With a specified lane width condition on the work zone and a speed limit one can easily compute how much network delay can be expected. Although the mathematical expression developed was case specific, the methodology that is highlighted is generic and can be applied for other micro-simulations as well. The scope of this research and data availability has limited the experimentation to static network modeling in VISSIM but a future research might be carried out using dynamic network modeling under similar or different circumstances.

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