Dynamic Simulation for Assessment of Impact of Highway Lane Closure on Traffic

Seokyon Hwang

Assistant Professor, Department of Civil Engineering, Lamar University, P.O. Box 10024, Beaumont, TX 77710. PH (409) 880-7557; FAX (409) 880-8121; e-mail: seokyon.hwang@lamar.edu

Abstract

Improvement of existing highway systems, such as maintenance, rehabilitation, and reconstruction, is accompanied with lane closure at work zones. Such lane closure causes road user costs for traffic congestion and delays at the work zones. A robust method is developed in this research to support strategic decision-making on lane closures. At this stage, the research focuses on a common situation—closing a segment of one lane in one direction on a four-lane highway. The method divides a work zone into arriving-, entering-, passing-, and leaving-zone and classifies the flow of vehicles as arriving-, in-, through-, and out-flow. Thereby, it accounts for traffic congestion and delay due to speed reduction, upstream queue, and speed recovery. Based on dynamic simulation technique, the method simulates the flow of vehicles and measures congestion and delay at work zones. The new method would benefit engineers in planning highway system improvement projects.

Keywords: Highway, Reconstruction, Lane closure, Congestion, Delay, Simulation

Introduction

In the United States, public expenditures have increased in recent years to renew and revitalize aging highway systems (U.S. DOT 2006) where most existing systems are deteriorating at a fast pace (ASCE 2002). Federal Highway Administration (FHWA) and state departments of transportation (DOTs) estimated the need of a huge amount of average annual capital investment in highways and bridges for the 20-year period 2005–2024: $78.8 billion for maintenance of the systems and $131.7 billion of maximum economic investment at all government levels (U.S. DOT 2006).

In addition to direct capital investment, highway improvement projects have a broader impact on the society. Such projects are inevitably accompanied with lane closure at work zones, either partially or completely. For instance, a certain length of stretch of a road needs to be closed to repair or replace deteriorated concrete pavement, which reduces the capacity of the road. As a result, traffic demand on the road can exceed the reduced capacity, which can incur traffic congestion and delay caused by speed reduction and queue of vehicles at the work zone (Carr 2000), and even complete failure of highway operations in the peak time periods (Martinelli and Xu 1996). This phenomenon ultimately can incur a considerable amount of public cost, such as delay cost and loss of business, and increased safety risk.

A robust method was developed in this research based on dynamic simulation technique to quantify the impact of lane closures on traffic at work zone. It evaluates the impact by means of measuring travel time of vehicles. Dividing a work zone into four sub-zones (arriving-, entering-, passing-, and leaving-zone), the method accounts for the effect of speed reduction, upstream queue, and speed recovery on traffic flow. The method simulates the flow of vehicles (arriving-, in-, through-, and out-flow) and measures travel time of vehicles passing through a work zone. Thereby, it accounts for feedback on dynamics among the flows.

The study presently focuses on one of the most common situations—closing a segment of one lane in one direction (single-lane closure) on a four-lane divided highway. Discussion in this paper focuses on the following findings: the strategies for the development of the method, a preliminary dynamic simulation model, and an application example for demonstration of the method.

Lane Closure Decision and Traffic

Theoretically, an unlimited number of ways of lane closure are possible to configure a work zone in a highway improvement project. Given a four-lane divided highway, the following exemplifies a few possible ways to configure a work zone: (1) closing one lane in one direction (single-lane closure), (2) completely closing two lanes in one direction and diverting all vehicles in that direction to the roadway in the opposite direction, and (3) completely closing two lanes in one direction and detouring all vehicles in that direction. Too many options, on the other hand, create the challenge of evaluating each option and selecting the best performing closure strategy. This pronounces the need for effective methods for quantification of impact of each strategy to evaluate various possible options for lane closure.

In the study of work zone problem, previous efforts have been concerned with a variety of issues associated with planning and operation of a work zone. Some representative issues include the following: the analysis of factors causing traffic congestion and delays at a work zone, the calculation of delays and user costs, the optimization of traffic control design and practices, the design and development of optimal control devices, and the optimal configuration of a lane closure strategy. Attempting to improve decision-making process while dealing with such challenging issues, various methods and approaches have been developed. The following briefly discusses a few representative studies.

Much effort has been devoted to improving accurate estimation of road capacity, delays, and user costs. Lane closure naturally decreases the design capacity of a road, thus, estimating capacity loss is important when planning a lane closure. Krammes and Lopez (1994) developed a computer model to estimate road capacity during maintenance work. Noting that reduced capacity at a work zone incurs delays caused by speed reduction and congestion, estimating traffic delays, user costs, and vehicle operating costs has been intensively studied (Mammoth and Dudek 1984; Dudek et al. 1986; Krammes et al. 1987; Carr 2000). In an attempt to optimize work zone length, traffic control design, and practices, various methods have been developed to compare and evaluate different lane closure strategies (Mahmassani and Jayakrishnan 1988; Chien et al. 2002; Chen and Schonfeld 2005).

Meanwhile, unlike the above technical solutions, administrative solutions also have been sought for. In an effort to mitigate traffic congestion and resulting impacts, the government agencies have adopted a variety of contracting methods, such as A+B contract and A+B+I/D (Herbsman 1995). These methods incorporate road user costs in project costs, aiming to reduce disruption to traffic so as to minimize the overall societal costs.

Method of research

Problem Context

Depending on traffic demand, congestion tends to occur during a certain time period of a day (Dudek et al. 1986). In other words, traffic congestion may occur in different scales under various situations at a work zone. For instance, demand may increase during the commuting time periods in urban freeways. Thus, it is important to estimate traffic congestion given various volumes of traffic over time. Measuring the number of vehicles traveling through a work zone for a particular time period, it is possible to evaluate the effect of lane closure on the road capacity at the work zone and the operation of the road during the time period.

With regard to traffic speed at a work zone, there are a few prevailing phenomena. (1) If there is congestion at a work zone, the speeds of vehicles decrease as vehicles approach to the area. (2) Even if there is no congestion, vehicles may have to slow down to comply with the limit of speed at the work zone imposed by law for safety of road workers and drivers. (3) The speeds of vehicles in a work zone eventually depend on how fast vehicles move out of the area and accelerate to normal speed to leave the work zone area. (4) The pattern of flow of a vehicle at and near a work zone affects the speed of the vehicle. (5) The length of a work zone can become an influential factor affecting congestion and delays (Martinelli and Xu 1996; Chen and Schonfeld 2005); thus, the length of a work zone should be taken into consideration when estimating the speed of a vehicle traveling the work zone and the amount of time the vehicle consumes in the area.

Behaviors of Vehicles and Work Zone Decomposition

Concerning the speed of traffic at a work zone, traffic normally exhibits three patterns of speed—slows down before the work zone, maintains reduced speed or even further slows down in the work zone, and slowly speeds up after the work zone. Considering these patterns, this research divided a work zone and its vicinity into arriving-, entering-, passing-, and leaving-zone. Meanwhile, the actual capacity of a work zone is determined by the flows of vehicles at four sub-zones discussed earlier. For instance, congestion is caused at entering-zone by the reduced flow of vehicles into the passing-zone. Therefore, the flows of vehicles, which are defined as arriving-, in-, through-, and out-flow, are basic information required to explain congestion and delays of traffic at a work zone that are caused by speed reduction, upstream queues, and speed recovery.

The following briefly explains each of the four flows. The arriving-flow represents the normal flow occurring before a work zone. Both in-flow and through-flow are influenced by congestion caused by accumulating vehicles in the passing-zone, which is due to reduced capacity and mandatory slow driving for safety. Finally, out-flow is dependent on congestion occurring at leaving-zone in which vehicles are recovering normal speed right after the work zone.

System Dynamics Modeling

System dynamics modeling is known to be a useful technique for translating the real-world systems and abstracting those into model elements by which the dynamics in the systems can be effectively explained. Elements and mechanisms of a model as well as flow of information among elements can be explicitly represented in a model (Hannon and Ruth 1997). The properties allow overcoming a significant shortcoming of the existing approaches to the lane closure problem. Existing methods generally deal with the delays due to congestion and the delays due to speed reduction in a work zone separately. System dynamics modeling allows modeling the dynamics existing in the system in a model, so that the resulting model can simultaneously deal with congestion, speed reduction, and queues of vehicles.

A system dynamics model comprises three kinds of system variables (Hannon and Ruth 1997). State variables indicate the current status of the system and represent the states of stocks flowing in the system. Flow variables represent changes to the states of stocks that happen as simulation runs. Transforming variables influence flow variables so as to make changes to the state variables.

Dynamic Simulation ModeL

System Variables and System Dynamics Model

The flow of traffic in and near a work zone is very dynamic. The dynamics can be attributed to feedback effect caused by the flows of vehicles at four sub-zones that are affected by congestion, speed reduction, and queues of vehicles. Table 1 presents the variables of the present model: state variables (number of vehicles at each zone), flow variables (flow of vehicles through each zone), and transforming variables (factors and controls influencing flows of vehicles). The demand of vehicle per minute (vpm) represents the number of vehicles arriving at a work zone per minute. Its distribution, both normal and reduced, can be obtained from vehicles per hour (vph) traveling the road. The distribution normally changes over time depending on actual demands at different time periods. In order to account for random arrivals of vehicles, the randomness is introduced to arrivingFlow and the random effect influences other flows followed by; more details are discussed in the following section. The maximum number of vehicles (maxVeh) represents the largest number of vehicles that are allowed to be in passing-zone any time periods. This parameter is assumed to be estimated by engineers in proportion to the length of the work zone (L), considering safety requirements such as limited work zone speed, road performance conditions, work layout, etc.

Figure 1 illustrates the developed system dynamics model, Dynamic-T (System Dynamics AssessMent of Impact of lane Closure on Traffic). One part of the model (double-lined box) simulates vehicle flow and the other part (single-lined box) collects cumulative number of vehicles that have passed through each flow. Using the flow rates of vehicles between the sub-zones, the model simulates and analyzes the flow of vehicles across the work zone. It also measures the volume of traffic passing through the work zone over time. A graphical dynamic modeling and simulation tool, StellaTM (iseesystems Inc. 1985), was used to construct and simulate the model.

Table 1. Variables of the Simulation Model

Type of variable	Variables
State variable	*vehArrived, vehInWZ;* *TOTALvehEntered, TOTALvehArrived, TOTALvehLeft*
Flow variable	*arrivingFlow, inFlow, outFlow;* *arriving, entering, leaving*
Transforming variable	*vpm, L, maxVeh, speedReduction, OnOff, AC1, AC2*

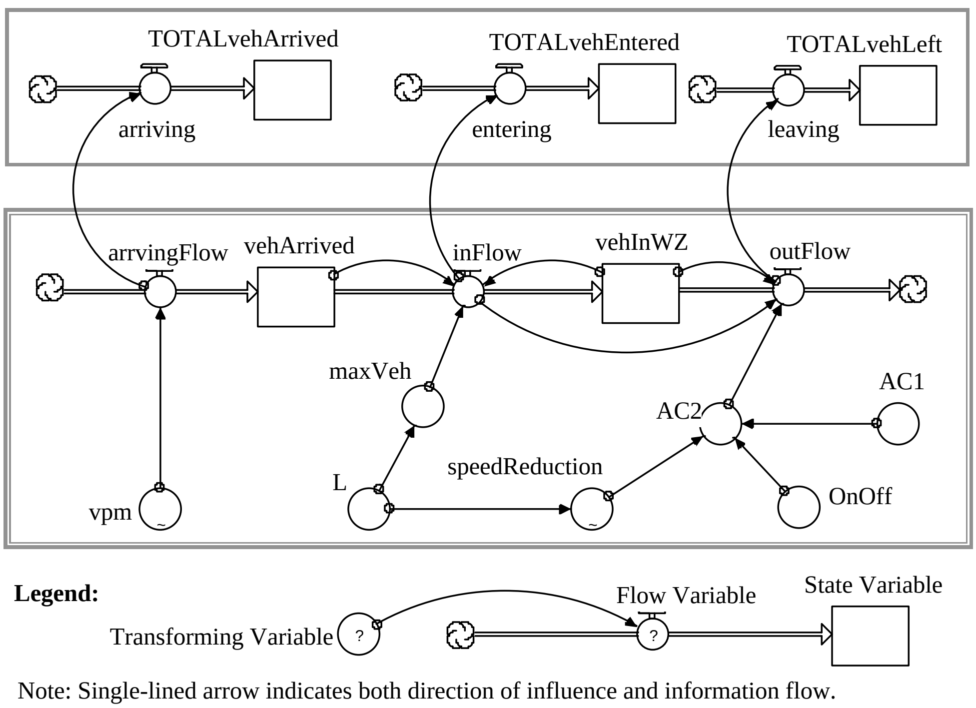


Figure 1. System Dynamics Simulation Model (Dynamic-T)

Simulation Algorithm

Arrival rate of vehicles normally is known to be random and represented by a certain distribution. While considering randomness, many queuing simulations adopt the Poisson distribution for arrival rate, assuming the average rate per interval time is known and fixed. Known the average rate from historical data normally is reported on a one-hour interval basis. The rate changes in time depending on various levels of demand at different time periods. In the new method, normal distribution is used to represent the arrival rate. It is not effective to apply a fixed arrival rate considering continuous change in demand, where the primary interest of the study is to assess continuously the impact of lane closure during a day, i.e., twenty four hours. Figure 2 presents the algorithm of the present simulation model. The flow of vehicles at each zone, except for *arrivingFlow*, is controlled by the state variables at *vehArrived* and *vehInWZ*, as well as the transforming variables, related to the flows. The *arrivingFlow*, the number of vehicles arriving per minute, is determined by the demand of vehicle per minute, *vpm*. Unless there is a natural decrease in demand or a planned decrease arranged by diverting vehicles before a work zone, *arrivingFlow* is clearly independent of any variables, but *vpm*. *vpm* data is normally acquired from historical data such as highway capacity report, which takes into consideration the ratio of trucks out of total demand.

The *inFlow* can be delayed by the state variable. *vehInWZ*, because the simulation does not allow more than a certain number of vehicles per unit length, *maxVeh*, in *vehInWZ*. For instance, engineers based on historical data may estimate that the number of vehicles in a work zone should not exceed eighty vehicles per mile for safety. The *inFlow* is affected by *arrivingFlow*, because it determines the state of *vehArrived* that controls the flow rate of vehicles at *inFlow*. The *inFlow* is also influenced by *outFlow*, because *outFlow* determines the state of *vehInWZ*. The through-flow, one of the four flows defined earlier, is not implemented in the simulation, because it is a conceptual flow occurring in *vehInWZ*, which is governed by *outFlow*. The more vehicles are in the *vehInWZ*, the longer a queue develops in entering-zone, and the less number of vehicles are allowed to flow at *inFlow*.

```
vpm = GRAPH(time)

vehArrived(t) = vehArrived(t - dt) + (arrvingFlow - inFlow) * dt
vehInWZ(t) = vehInWZ(t - dt) + (inFlow - outFlow) * dt
arrvingFlow = normal (vpm, vpm*.05)
inFlow = IF (vehInWZ<=maxVeh) THEN (IF (vehArrived>(maxVeh-vehInWZ)) THEN (maxVeh-vehInWZ)
        ELSE (vehArrived)) ELSE (0)
outFlow = IF(inFlow<=AC2) THEN inFlow ELSE IF vehInWZ>AC2 THEN AC2 ELSE vehInWZ

TOTALvehArrived(t) = TOTALvehArrived(t - dt) + (arriving) * dt
TOTALvehEntered(t) = TOTALvehEntered(t - dt) + (entering) * dt
TOTALvehLeft(t) = TOTALvehLeft(t - dt) + (leaving) * dt
arriving = arrvingFlow
entering = inFlow
leaving = outFlow

AC2 = IF OnOff=1 THEN AC1*speedReduction ELSE AC1
speedReduction = GRAPH(L)
maxVeh = 80*L
```

Figure 2. Simulation Algorithm

It is assumed that the road capacity at a work zone can be reduced due to the limit of speed the zone, *speedReduction*, and the decreased vehicle speed for the loss of one lane, *AC1*. Both parameters are to be determined by engineers based on existing historical data, for instance, published data by DOTs. The *OnOff* allows switching s*peedReduction* from active to inactive, and vice versa, in calculating the augmented capacity reduction, *AC2*. The *AC2* is determined by considering speed limit, capacity reduction for reduced number of lanes, and the length of lane closure.

Output and Analysis

The simulations of a work zone with the model produce many informative outputs, including the number of vehicles passing each sub-zone during individual periods and over time. Interpreting these data, engineers can produce important information with regard to the impact of lane closure on traffic and highway system operation during construction. Both are useful to estimate service level of the road for different demand over time by measuring traffic congestion and delays at different time periods of a day. In this manner, engineers can evaluate each lane closure strategy among many possible candidates by quantifying its impact on traffic. To name a few decisions that can be effectively made by using such information, it includes the length of lane closure, time to impose speed limit, if flexibly operated, and time to start work at a work zone. Additionally, the data can provide information on the volume of vehicles to be detoured to maintain a certain level of service.

A Hypothetical Example

A hypothetical situation was created for demonstration of the new method. A set of input data—road capacity, speed of vehicle, and traffic demand—was prepared based on published data in the Highway Capacity Manual (TRB 1985). Other parameters were assumed to be estimated by engineers.

Situation

A segment of a lane needs to be closed to replace existing pavement on a four-lane divided highway. At the work zone, traffic in two lanes merges into one open lane, and diverting or detouring traffic is not considered. Recent data samples show that the average hourly demand varies over time during a day. Vehicles using the road comprise 25% of truck and 75% of cars. Figure 3 depicts the relationship between the length of lane closure (L) and the reduction of vehicle speed (speedReduction), for which data is acquired from a recent survey. Figure 4 (a) presents the distribution of traffic demand during a day. The demand of vehicle per minute is calculated from vehicle per hour. According to historical hourly capacity data, the average capacity of one lane in one direction is 1500 vph that is equivalent to 25 vpm, without any speed limitation in the work zone. Engineers consider two lane closure strategies in terms of the length of closure—2 miles and 5 miles. Running the simulation for 24 hours (1,440 minutes) with 1 minute interval, the following results were obtained.

Results

Figure 4 (b) and (c) illustrate the results of two cases—2 mile and 5 mile long lane closures. Briefly discussing the results, the longer lane closure resulted in more congestion and delays. For both cases, traffic started building up a queue from the moment that demand exceeds capacity. The queue was transferred to the next time periods and started to decrease when demand becomes smaller than capacity. With 2 mile long closure, traffic congestion was observed two times, 7 - 10 a.m. and 6 - 11 p.m., whereas congestion was observed almost a whole day with 5 mile long closure, 7 a.m. - 12 a.m. Decision of choice can be made depending on the threshold of acceptable congestion level that is set by engineers.

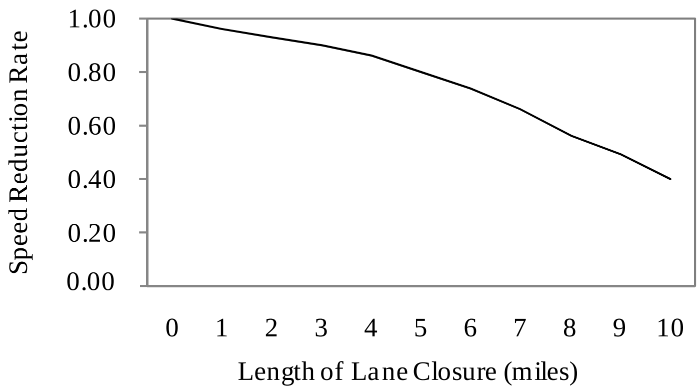
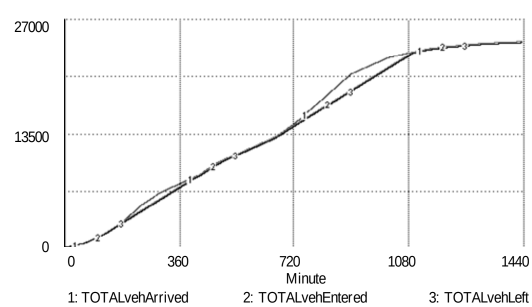


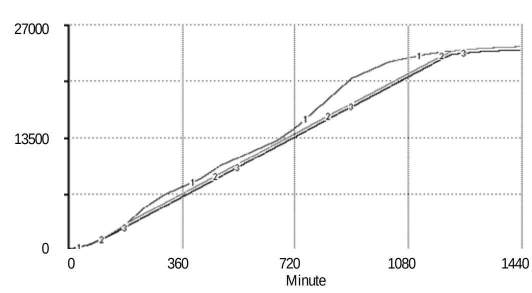
Figure 3. Relationship of *speedReduction* and Length of Lane Closure (*L*)

Minutes	Time of Day	Vehicle Per Hour (vph)	Vehicle Per Minute (vpm)
0	A.M. 5	500	8.33
60	6	1000	16.67
120	7	1500	25.00
180	8	2000	33.33
240	9	1500	25.00
300	10	1000	16.67
360	11	1000	16.67
420	P.M. 12	1500	25.00
480	1	1000	16.67
540	2	1000	16.67
600	3	1000	16.67
660	4	1500	25.00
720	5	2000	33.33
780	6	2000	33.33
840	7	2000	33.33
900	8	1000	16.67
960	9	1000	16.67
1020	10	500	8.33
1080	11	500	8.33
1140	A.M. 12	300	5.00
1200	1	200	3.33
1260	2	200	3.33
1320	3	100	1.67
1380	4	100	1.67
1440	5	300	5.00

(a) Demand Over Time



(b) *L*=2 miles



(c) *L*=5 miles

Figure 4. Results of an Application Example

Conclusions

Highway projects for keeping or enhancing the existing systems presents a broad impact to the society. Accompanied lane closure at a work zone seriously causes the capacity reduction, which in turn incurs speed reduction and resulting traffic congestion and delays. Such undesirable situation creates tremendous amount of road user costs, in addition to construction costs. Thus, a strategic decision on lane closure is needed to reduce the congestion and delays. When planning improvement projects, engineers need to be able to estimate the amount of impact of various configuration of lane closure. A robust method was developed based on system dynamics simulation technique. The method is envisioned to be a useful tool for decision-making in designing and operating lane closure at a work zone. The method is effective to estimate congestion and delays by measuring and analyzing traffic flows across a work zone. It is effective in identifying and measuring traffic congestion and delays over time under various situational demand of traffic. In addition, the simulation model simplifies the process of the evaluation of lane closure strategies.

Developed method requires situational demand over time, which is manually provided for simulations. In future, the task needs to be automated so that engineers can test a variety of situational demand without paying much effort on creating data sets. The present research initiative can also be extended further to encompass more lane closure strategies and configuration. Developing a model for each of those may require additional modeling activities. However, findings from the present study can provide a strong foundation. Additionally, the problem scope can be extended to look into the work zone problem from a broader perspective. In order to find a solution to minimize the broader impact, it is necessary to take into consideration direct construction costs, traffic control costs, accident costs, road user costs, and safety and productivity on the job site.

References

[1] American Society of Civil Engineers (ASCE). (2002). "Report card: Reports and statistics." <http://www.asce.org/reportcard/>.

[2] Carr, R. I. (2000). "Construction congestion cost (CO) basic model." J. Construction Engineering and Management, 126(2), 105-113.

[3] Chen, C., and Schonfeld, P. (2005). "Work zone lengths for a four-lane road with an alternate route." J. Transportation Engineering, 131(10), 780-789.

[4] Chien, S., Tang, Y., and Schonfeld, P. (2002). "Optimizing work zones for two-lane highway maintenance projects." J. Transportation Engineering, 128(2), 145-155.

[5] Dudek, C. L., Richards, S. H., and Buffington, J.L. (1986). "Some effects of traffic control on four-lane divided highways." Transportation Res. Rec. 1086, 20-30.

[6] Hannon, B., and Ruth, M. (1997). Modeling dynamic biological systems. Springer, New York.

[7] Herbsman, Z. J. (1995). "A+B bidding method - hidden success story for highway construction. " J. Construction Engineering and Management, 121(4), 430-437.

[8] iseesystems Inc. (1985). Stella v 8.1 <http://www.iseesystems.com>.

[9] Jaraiedi, M., Plummer R. W., and Aber, M. S. (1995). "Incentive/distincentive guidelines for highway construction constracts." J. Construction Engineering and Management, 121(1), 112-120.

[10] Krammes, R. A., and Lopez, G. O. (1994). "Updated capacity values for short –term freeway work zone lane closures." Proc., TRB 73rd Annual meeting, Transportation Research Board, Washington, D.C.

[11] Krammes, R. A., Marsden, B. G., and Dudek, C. L. (1987). "Micor-computer tool for freeway work zone planning and scheduling." J. Transportation Engineering, 113(4). 348-356.

[12] Mahmassani, H. S., and Jayakrishnan, R. (1988). "Dynamic analysis of lane closure strategies." J. Transportation Engineering, 114 (4), 476-496.

[13] Mammoth, J. L., and Dudek, C. L. (1984). "Queue and cost evaluation of work zones (QUEWZ)." Transportation Research Board, Washington, D.C., 12-19.

[14] Martinelli, D. R., and Xu, D. (1996). "Delay estimation and optimal length for four-lane divided freeway workzones." J. Transportation Engineering, 122(2), 114-122.

[15] Transportation Research Board. (TRB). (1985). Highway capacity manual, Special Rep. No. 209, TRB, Washington, D.C.

[16] U.S. Department of Transportation (U.S. DOT). (2006). Status of the nation's highways, bridges, and transit: 2006 Conditions and performance, <http://www.fhwa.dot.gov/policy/2006/>.