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Effect of Variable-Message Signs in Reducing Railroad Crossing Impacts

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At-grade highway–railroad crossings cause traffic control problems that have a bearing not only on traffic safety but also on traffic flow efficiency. Crossings located near freeway exits pose particularly acute problems, as long closures could result in vehicle queues that spill back onto freeway lanes. A potential solution to this problem was evaluated by investigating the use of variable message signs to divert exiting freeway traffic through non-congested alternate exits. This was done using the crossing near the Fredericksburg Road exit on Interstate 10 (I-10) in San Antonio, Texas, as a case study. In the evaluation, microscopic simulation was used to determine the impacts of train operations at the crossing and the potential benefits of a variable-message sign (VMS) system installed on I-10. These effects were gauged by considering scenarios with varying levels of train duration, traffic demand on the freeway exit, and driver compliance to the displayed messages. While little network improvements were obtained, the analysis demonstrates the capability of the INTEGRATION software in analyzing such scenarios and the extent to which exiting freeway traffic may benefit from the VMS system, as well as the need to consider fuel consumption and vehicles emissions in the evaluations.

At-grade highway–railroad crossings create safety concerns for the crossing vehicular traffic and affect traffic flow performance each time a passing train blocks traffic movements across the rail tracks. The impact of the delays generated during these blockages is particularly pronounced in urban areas, where long freight trains running at low speeds often result in railroad crossings being closed for several minutes. Crossings in the vicinity of urban freeways are even more problematic. At these locations, the closing of frontage streets for several minutes can prevent traffic from entering the freeway and even block the exiting traffic. Eventually, these blockages can result in traffic congestion on freeway feeding streets as well as on freeway exit lanes.

To alleviate the severity of the problems posed by crossings located near freeway exits, the San Antonio Metropolitan Model Deployment Initiative attempted to integrate highway–rail interfaces with various forms of traveler information. In one case, the Advance Warning for Railroad Delays (AWARD) proposed the use of variable-message signs (VMSs) to warn freeway traffic about freeway exit blockages by passing trains at three locations along Interstate 10 (I-10) in San Antonio, Texas (*1*). The aim of this system was to help motorists and emergency vehicles avoid delays caused by railroad operations on tracks crossing freeway–frontage access roads.

Using one of the AWARD intersections as a case study, this paper investigates the potential of using VMSs to reduce the delays incurred by motorists at railroad crossings near freeway exits. A second objective is to evaluate the potential of VMSs to improve traffic performance near freeway exits as measured by fuel consumption and vehicle emissions. This investigation is conducted by first reviewing the conclusions drawn by previous research efforts on at-grade highway–railroad crossings. This review is followed by a description of the railroad crossing that was used in this case study. The next five sections then successively present the study approach, the simulation modeling of the case-study intersection, the various scenarios considered, the results of the evaluations, and the main conclusions of the analysis.

LITERATURE REVIEW

Numerous studies have been made on the subject of at-grade highway–railroad crossings. While most deal with the safety problems associated with the operation of such crossings, only a few have addressed the impact of at-grade crossings on traffic performance within urban street networks. In particular, few studies have attempted to evaluate the impact of train operations near signalized intersections. Similarly, little research is found on subjects dealing with the initiation of diversion strategies in response to traffic congestion caused by the passage of freight trains, express passenger trains, and light-rail trains (LRT) at railroad crossings in urban networks.

One of the few studies addressing the effects of train operations in urban areas was performed by the Texas Transportation Institute (*2*). In this study, analytical tools were developed for evaluating the operation of LRT systems at crossings within urban signalized networks and to assess the overall impact of these systems on urban traffic performance. In another effort, Zhang and Hobeika (*3*) extended the CORSIM traffic simulation model to networks with highway–railroad crossings and tested the resulting model on a road network in Long Island, New York, covering three railroad crossings.

In the area of freeway operations, many researchers have evaluated the effects of implementing diversion strategies in response to traffic incidents and traffic congestion (*4–7*). However, no research addressing the diversion of freeway traffic in response to the closing of railroad crossings near freeway exits has been found. This lack of research thus outlines the uniqueness of the evaluation conducted in this paper.

CASE STUDY

To evaluate the potential of using VMSs to improve traffic performance at railroad crossings located near freeway exits, the Fredericksburg Road–Woodlawn Avenue railroad crossing near

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Exit 567 on I-10 in San Antonio, Texas, was selected as a case study. As indicated earlier, this crossing is part of the San Antonio AWARD system, which was designed to help motorists and emergency-response vehicles avoid delays caused by railroad crossings on freeway-frontage access roads.

The AWARD system uses Doppler radar sensors placed at selected locations along the section of the Union Pacific Kerrville rail line near I-10 to detect the presence, speed, and length of trains before they approach grade crossings. After detection of a train, data from the sensors are transmitted to the TransGuide Control Center, where computer algorithms calculate the predicted time and duration of freeway-exit blockage. Finally, this information enables operators to send messages to VMSs placed at strategic locations along I-10 to alert freeway motorists of potential delays ahead and allow them to avoid the congested area by selecting alternate exits.

At the Fredericksburg Road crossing, there are typically only two to three trains crossing on a given day, with usually one crossing around noon and another one at about 4:30 p.m. On some days, however, there can be up to seven train crossings. The duration of each crossing also usually varies from 3 to 7 min, with traffic blockage from 5 to 7 min and delays of up to 10 min often reported by motorists. These long blockages are due to trains constrained to operate in this vicinity at speeds of 16 km/h for safety reasons.

However, while the Fredericksburg Road crossing is part of the AWARD system, messages about exit blockages are currently rarely displayed on the I-10 VMS system. According to field interviews conducted in October 1998, messages are displayed only to warn motorists about unusual activities. This is explained by the fact that, while queues of vehicles often form on the freeway exits during railroad crossing closures, these queues rarely extend onto the freeway lanes.

While current traffic conditions provide no compelling need for using the I-10 VMS system to warn freeway motorists about regularly occurring queuing on the Fredericksburg Road exit, such use may become beneficial in the future if significant traffic growth occurs. In the more immediate future, the use of the VMS system to alert exiting freeway traffic about congestion problems at the Fredericksburg Road crossing may also improve local traffic conditions and network performance. This is what this paper intends to investigate.

STUDY APPROACH

The crux of the research reported in this paper is based on the premise that the impact of railroad-crossing closures on traffic flow in the vicinity of freeway exits can best be analyzed and evaluated using simulation. For this study, the INTEGRATION microscopic traffic simulation model (*8, 9*) was selected as the tool of choice for a number of reasons. First, this model, which was conceived during the mid-1980s as an integrated simulation and traffic assignment model (*10–14*), has been effectively used by a number of private engineering firms and public transportation agencies for the evaluation of various transportation projects (*15–18*). Consequently, the software is accepted by a wide audience of transportation professionals. Second, the fact that the INTEGRATION software explicitly models dynamic traffic assignment as opposed to assigning turn probabilities at nodes, which is what is commonly used in other microscopic simulation software including CORSIM and VISSIM, the model can provide output that is origin–destination (O–D) specific. This key advantage evolves from the fact that the INTEGRATION software, unlike most microscopic software, tracks individual vehicles from their point of origin to their final destination (*19*). Third, the INTEGRATION software provides the flexibility of explicitly modeling VMSs for different levels of compliance and explicitly models driver-dynamic traffic diversion. Fourth, the INTEGRATION model uses state-of-the art vehicle fuel-consumption and emission models, as is described in detail in the literature (*19*). These unique features of the INTEGRATION software are briefly discussed in the following paragraphs. For more information on the INTEGRATION software, the reader is directed to other literature sources (*19*).

Among the unique features of the INTEGRATION model is the use of the same traffic-flow logic to represent both freeway and signalized links. The model also uniquely features simulation and multipath–multiuser traffic-assignment components that are microscopic, integrated, and dynamic. Simulation with the model involves the tracking of individual vehicle movements from a vehicle's origin to its destination at an update rate of up to once every 0.1 s. This microscopic approach permits the detailed analysis of many traffic phenomena, such as shock waves, gap acceptance, and weaving behavior. It also permits considerable flexibility in representing spatial variations in traffic conditions. The dynamic approach adopted by the model further allows it to consider virtually continuous time-varying demands, routings, link capacities, and traffic controls without the need to predefine an explicit common time-slice duration. This implies that the model is not restricted to hold departure rates, signal timings, incident severities, and even traffic routings at a constant setting for any particular period of time. Finally, the INTEGRATION model can be used not only to estimate stops and delays, but also to estimate vehicle fuel consumption and emissions within a simulated network (*19–21*). Embedded in the model are routines that compute the fuel consumption and emissions of hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) of each simulated vehicle on a second-by-second basis based on the vehicle's instantaneous speed and acceleration levels. The effect of the railway crossing on traffic safety was not evaluated in this study but is currently being evaluated and will be presented in a separate publication.

To evaluate the impact of train operations at the Fredericksburg Road crossing, two calibration efforts were conducted. The first calibration effort involved calibrating the O–D demand to field conditions, while the second calibration effort involved calibrating the network supply to ensure consistent speeds and queues between the simulation and field conditions. The calibration efforts are described briefly in the following paragraphs.

The calibration of the O–D demand was conducted using a maximum likelihood synthetic O–D estimator using link counts from loop detectors located on the freeway and the freeway on-and off-ramps. Specifically, the QUEENSOD model (*22*) was used to perform this task. While the details of the model are provided in the literature (*22*), it is sufficient to note that the model was developed to support the INTEGRATION software by estimating the most likely O–D traffic demand for a network based on observed-link traffic flows and turning-movement counts, if available. The main advantage behind its use is that it shares the same data-file structures and file formats as INTEGRATION, thereby simplifying many analysis tasks.

The calibration of the supply involved calibrating the speed–flow relationship to ensure that simulated travel speeds and queue formations were consistent with field conditions. Once the base simulation run was calibrated, several simulation runs were conducted. In these simulations, instead of assuming that warning messages were displayed on the I-10 VMS system only when queues of vehicles on the freeway exit ramps were expected to spill onto freeway lanes, it was assumed that messages were displayed as soon as a train blockage was expected to occur. This more comprehensive approach was taken to fully evaluate the potential benefits of the system in reducing traffic congestion and improving traffic flow at the railroad crossing.

SIMULATION MODEL SETUP

To perform the evaluations, the road network of Figure 1 was coded in both QUEENSOD and INTEGRATION. This network covered approximately 1 mi^2 and included 15 O–D nodes. Details of the railroad-crossing modeling are shown in the upper left corner of the figure. As can be observed, train operations within the study area were simulated only for a small segment around Fredericksburg Road and Woodlawn Avenue. While the tracks continue in reality parallel to I-10 for some distance in both directions, there was no need to model a larger segment of the railroad tracks, as there are no at-grade crossings at the other major streets within the study area.

Within INTEGRATION, routing of background vehicles was applied using the Frank–Wolfe macroscopic traffic-assignment algorithm (*23*). The O–D flows required to perform these assignments were determined using loop-detector data collected at eight detection stations along the I-10 corridor. The data were collected at four mainline freeway stations, two off-ramp stations, and two on-ramp stations for eight 15-min intervals during the morning peak travel period. Following the data collection, a two-step process was used to compute the required O–D flows. In the first step, average hourly traffic counts were determined for each detection station using all 15-min traffic counts. In the second step, the resulting average hourly traffic counts from all detection stations were inputted into QUEENSOD to generate typical morning O–D flows for the simulated network of Figure 1. Table 1 presents the results of these calculations in the form of hourly average flows between each modeled O–D pair. At this point, it is important to note that simulations were performed assuming that demand does not change with time.

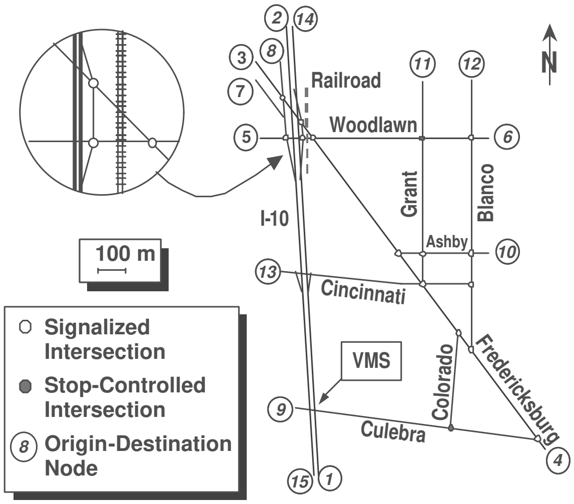


FIGURE 1 Integration simulation network.

For the purpose of the study, only vehicles traveling on I-10 West were assumed to exit the freeway. This assumption was made to account for the fact that messages displayed on the modeled VMS system would only affect vehicles traveling in that direction. As a result, only the flows between the O–D pairs 1-6, 1-11, and 1-12 in the network of Figure 1 are assumed to respond to the VMS system, as these vehicles are the only ones to exit the freeway and cross the Fredericksburg Road crossing in the absence of trains.

In addition to the flows in Table 1, bus flows were estimated separately and incorporated directly into INTEGRATION. These flows were included in an attempt to depict existing traffic conditions as accurately as possible. A separate analysis was made for these flows, as their characteristics could be easily determined from field observations and published transit schedules. Based on such observations, buses were coded to run on Fredericksburg Road only, at a rate of 20 vehicles per hour (vph). These flows must therefore be added to those of Table 1 to obtain the complete demand being simulated.

Trains were finally modeled by introducing a short fictitious highway link that crosses both roadways at the location of the existing train tracks. The simulation of traffic blockage by a passing train was then accomplished by discharging a heavy volume of traffic on the fictitious link. In this process, the duration of train crossing was controlled by suitably varying the start and end times of the traffic discharge. The stoppage of crossing vehicular traffic during each train crossing was handled by simulating the presence of "Yield" traffic signs on the roads crossing the rail tracks and by suitably adjusting the size of the minimum acceptable gap between successive train cars for vehicles attempting to cross the stream of vehicles, emulating the passage of a train. Alternatively, incidents completely blocking all traffic lanes located at the railroad crossings for the entire train-crossing duration could have been modeled.

Within the study area, the VMS system was modeled as being positioned in such way that vehicles intending to Exit I-10 at Fredericksburg Road could be rerouted through the upstream Cincinnati Avenue exit. Vehicle response to the displayed messages was then modeled by allowing vehicles to update their minimum travel-time path after passing the location of the VMS system using real-time information about current-link travel times. To ensure that only vehicles traveling between the O–D pairs 1-6, 1-11, and 1-12 would respond to the displayed messages, these flows were modeled using a different vehicle class than was specified as the only being affected by the VMS system. The compliance of each vehicle to the displayed messages was finally modeled through features of the INTEGRATION model that allow the user to specify various response levels to the availability of advance traveler information.

EVALUATION SCENARIOS

Table 2 lists several scenarios that were developed to study the effect of passing trains on traffic exiting I-10 at the Fredericksburg Road exit and to evaluate the benefits of using VMSs to warn incoming freeway traffic about exit blockages due to passing trains. These

TABLE 1 Estimated Current O–D Demand

Origin node (1)	Hourly average flow to destination node														
	1 (2)	2 (3)	3 (4)	4 (5)	5 (6)	6 (7)	7 (8)	8 (9)	9 (10)	10 (11)	11 (12)	12 (13)	13 (14)	14 (15)	15 (16)
1	–	0	38	18	38	41	0	0	18	18	41	41	18	1854	29
2	0	–	0	0	0	0	0	0	0	0	0	0	0	0	2748
3	0	0	–	10	10	10	0	0	10	10	10	10	10	14	48
4	0	0	56	–	10	10	0	0	0	10	10	10	10	30	46
5	0	0	10	34	–	34	0	0	34	34	34	34	34	14	48
6	0	0	56	10	10	–	0	0	10	10	10	10	10	30	48
7	0	0	10	34	10	34	–	0	34	34	34	34	34	14	48
8	0	0	10	10	10	10	0	–	10	10	10	10	10	14	48
9	0	0	56	10	10	10	0	0	–	10	10	10	10	30	46
10	0	0	56	10	10	10	0	0	10	–	0	10	10	30	46
11	0	0	56	10	10	10	0	0	10	10	–	0	10	30	48
12	0	0	56	10	10	10	0	0	10	10	10	–	10	30	48
13	0	0	56	10	10	10	0	0	10	10	10	10	–	30	46

NOTE: Origin-Destination pairs directly affected by the train crossings and the VMS system are 1-6, 1-11 and 1-12.

scenarios were designed to reflect real-life situations and to allow sensitivity analyses to be performed on factors such as train crossing duration, level of traffic demand, and level of driver compliance to VMS systems.

As indicated in Table 2, the first part of the analysis looked at the impacts of various train crossing durations. In this case, train durations varying from 0 min (no train) to 7 min were considered. This range is reflective of field observations, which indicate that trains often block the Fredericksburg Road crossing for periods of 5 to 7 min (*24*). For all following analyses, however, an average 6-min roadway closure is considered.

For the second portion of the analysis, scenarios considering different levels of traffic demand were generated. To remain realistic, only increases in flows exiting I-10 at the Fredericksburg Road exit were considered in this case. The study considered more specifically increases in exiting traffic of up to 50% above the current level, at increments of 5%. Such an increase would correspond to the passage of an additional 61 vehicles on the exit over each hour of simulation, a situation that could occur as a result of the stochastic nature of traffic, if another exit or a frontage road was closed due to construction or if an incident occurred downstream of the exit.

The above variations in traffic demands were considered not only to evaluate the sensitivity of the impacts of train operations on traffic-flow performance but also to evaluate the potential benefits of the VMS system when queues of vehicles caused by the closure of the Fredericksburg Road crossing threaten to spill onto the freeway lanes. As explained earlier, while queues of vehicles often form on the freeway exit during crossing closures, these queues currently rarely extend onto the freeway lanes. In particular, this situation is consistent with simulation results using estimated current demands, which show that the queues of vehicles forming on the Fredericksburg Road exit typically never affect freeway operations. Consequently, increased flows must be considered to enable the analysis of scenarios with queue spillbacks.

While the use of up to a 50% increase in traffic demand may seem unreasonable, available traffic-detector information indicates significant stochastic traffic variability that validates this choice. As an example, Figure 2 illustrates 15-min counts that were obtained from a detection station on I-10 West immediately upstream of the Fredericksburg Road exit. The figure shows 15-min counts for four consecutive periods during the morning peak travel period for three sets of five consecutive days, together with the average counts for each day. The figure also illustrates the average demand used in the

TABLE 2 Simulation Scenarios

Scenarios (1)	Exit Demand Level (%) (2)	Duration of Train Crossing (min.) (3)	VMS Active (4)	VMS Response Level (%) (5)
1-8	100	0 to 7	No	-
9-20	100-150	6	No	-
21-30	100	6	Yes	0-100
31-40	125	6	Yes	0-100
41-50	150	6	Yes	0-100

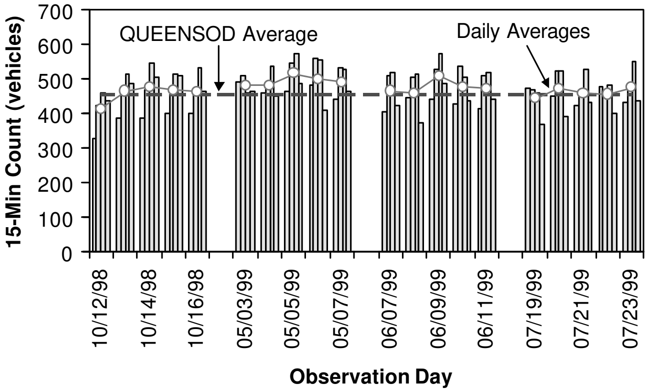


FIGURE 2 Traffic variability on I-10 West between 7:00 and 9:00 a.m.

generation of O–D flows with the QUEENSOD model, which was based solely on the October 1998 traffic counts. As observed, there was significant variability in traffic flow within each day. In particular, it was observed that the peak 15-min demand exceeded the hourly peak demand by more than 10% for most of the days. In addition to the variability within the peak period, significant variability was also observed from one day to the next. As an example, traffic counts from May 1999 yielded hourly flow estimates that were 5% to 13% higher than the average flows used in QUEENSOD to characterize current traffic conditions. Due to the stochastic nature of traffic, traffic within a peak 15-min period may thus easily vary by up to 25% relative to the demand coded for the simulation analyses.

In the final analysis, driver compliance to the VMS system was varied from 0 to 100%, in increments of 5% intervals, for scenarios considering either current demands or a 25% increased demand at the Fredericksburg Road exit. While it is uncertain whether compliance levels in excess of 50% could currently be attained at the study site, such a wide range of vehicle response levels was considered with the simple objective of better analyzing the trend of potential benefits.

For each scenario, finally, simulations were performed using a two-step process. In the first step, the study network was loaded with the corresponding demand and simulated for a 1-h period. Following this initial period, the network was simulated for another hour with no added demand, to ensure that all the vehicles that entered the simulated network during the first hour of simulation cleared the network before compiling performance measures. Ten replications were also made for each scenario to account for the stochastic variability of simulation outputs from the INTEGRATION model. Thus, unless otherwise noted, the performance measures reported in the remaining sections of the paper are for an average of ten distinct evaluation runs.

SIMULATION RESULTS

Figure 3 illustrates the results of the simulations that were conducted to evaluate the impacts on traffic performance of train operations at the Fredericksburg Road crossing. The various diagrams shown in the figure illustrate the changes in travel time, fuel consumptions, and emissions of HC, CO, and NO_x that result from the passage of trains of various lengths. In addition, each diagram illustrates both the networkwide impacts and impacts on exiting freeway vehicles with travel paths going across the railroad crossing (traffic between O–D pairs 1-6, 1-11, and 1-12).

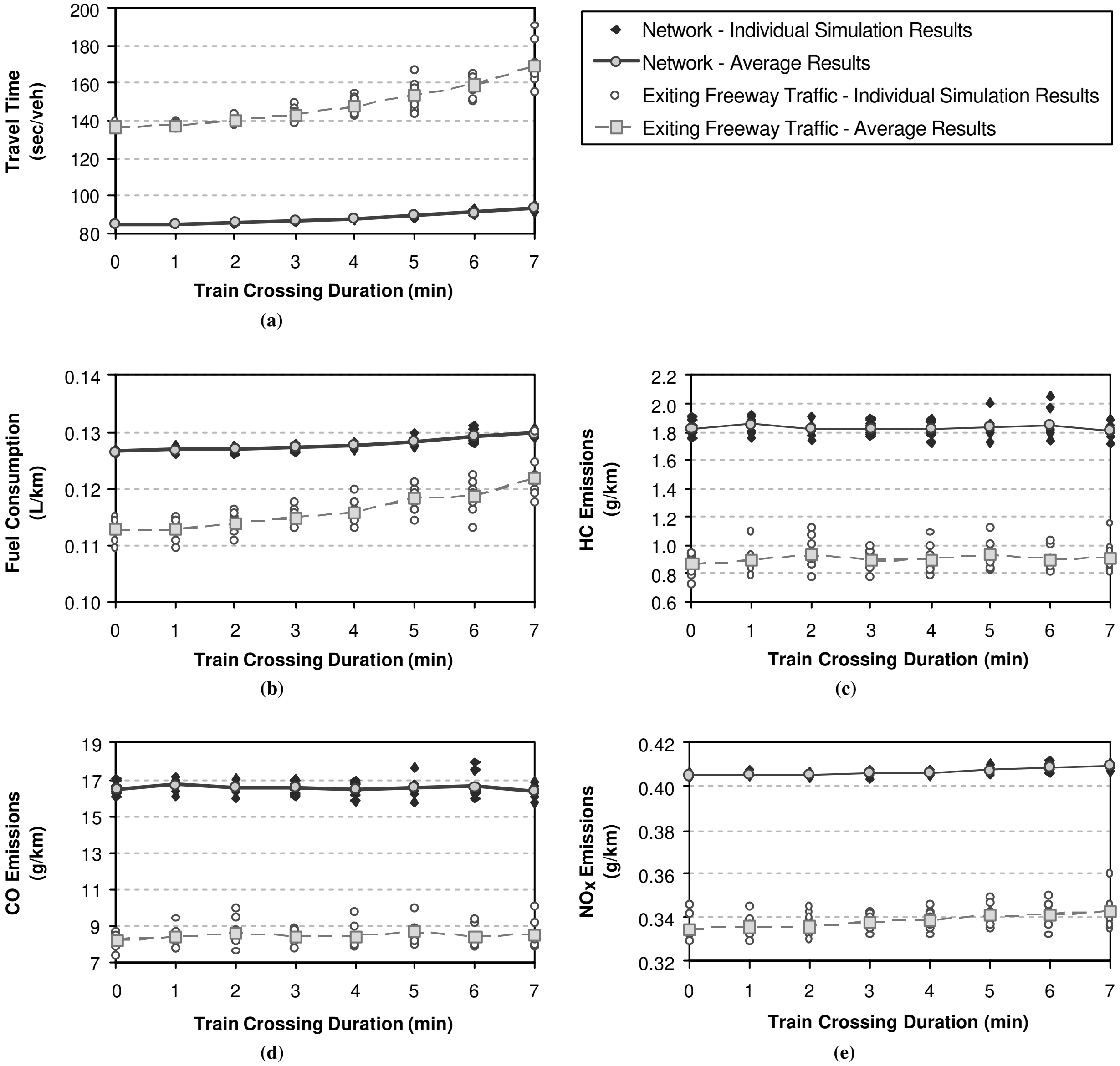
In the various diagrams of Figure 3, it is observed that train operations have a certain impact on traffic-flow performance. For instance, when compared with a situation with no train operations, it is observed that the passage of an average 6-min train causes a 7.4% increase in total network travel time, a 2.1% increase in fuel consumption, and increases in vehicle emissions ranging between 0.9% and 1.3%. All these changes are significant at the 90% level, except for the increases in HC and CO. For the exiting freeway traffic going across the railroad crossing, the passage of a 5-min train causes a 16.0% increase in average travel time, a 5.3% increase in fuel consumption, and increases of HC, CO, and NO_x of 4.0%, 2.4%, and 1.9%, respectively. Again, these changes are all significant, except for the HC and CO emissions. In terms of delay, the travel-time increase translates at the network level into an additional average delay per vehicle of 6.3 s and, for the exiting freeway traffic, into an additional average delay per vehicle of 22.0 s.

In the figure, the lack of significant impacts on HC and CO emissions is explained by the fact that vehicle emissions do not depend only on total travel time but also on the speed and acceleration profiles associated with each trip. While increases in travel speed tend to result in increases in fuel consumption and emissions, speed variability and, particularly accelerations at high speeds, can contribute significantly more to the total fuel consumed and pollutant emitted by a vehicle. This is particularly true for the HC and CO emissions, which are typically more sensitive to speed variability than are fuel consumption and NO_x emissions. Consequently, modifications in the speed profiles of vehicles caused by the closing of the railroad crossing and the subsequent queuing of vehicles of Fredericksburg Road and Woodlawn Avenue can explain the various trends observed in Figure 3. Thus, while longer delays may result from the closing of the crossing, smoother speed profiles that cause lower HC and CO emissions may also result from it.

While there is no doubt that exiting freeway vehicles blocked at the railroad crossing during the passage of a train contribute to the networkwide impacts that are observed in Figure 3, a detailed analysis of the simulation results also indicates that nonfreeway traffic being queued on Fredericksburg Road and Woodlawn Avenue during the passage of a train also significantly affects the networkwide performance measures. Typically, the exiting freeway traffic accounts for only 6% of the total network increase in travel time and for less than 1% of the observed changes in fuel consumption and emissions. This is due to the relatively low volume of vehicles exiting the freeway and crossing the railroad (123 vph) with regard to the total number of vehicles simulated (7,216 vph). Nonetheless, the results of Figure 3 clearly indicate an impact on exiting freeway traffic, and thus, potential benefits that could be obtained by using the exiting I-10 VMS system to warn exiting freeway traffic about blockages by trains at the Fredericksburg Road exit.

Figure 4 illustrates the sensitivity of network travel times to the level of traffic exiting the freeway at the Fredericksburg Road exit. As expected, the figure indicates that increases in exiting traffic demand generally result in travel time increases. However, these increases remain relatively small. For instance, an increase in total network travel time of only 2.0% is observed when the exiting flow is increased by 50%. Similar results are found when fuel consumption and vehicle emissions are compiled. In this case, a 50% increase in exiting traffic demand causes an increase in network fuel consumption of only 1.4% and increases in HC, CO, and NO_x emissions of only 1.7%, 1.5% and 1.2%, respectively. This result is again attributable to the small number of exiting vehicles in relation to the total number of simulated vehicles. In this case, an increase of 50% in exiting traffic demand adds only 61 vph to the network, which corresponds to a network traffic-demand increase of only 0.85%.

An element of particular interest in the above results is the fact that the percentage increases in network travel time, fuel consumption, and vehicle emissions are all greater than the increase in overall demand. While the maximum overall demand increase does not exceed 0.9%, increases in total travel time, fuel consumption, and vehicle emissions range from 1.2% to 2.0%. These results are attributed to the changes in traffic-flow dynamics that occur within the network as a result of the increased congestion caused by the added vehicles. This observation emphasizes the need to consider



(a)

(b) (c)

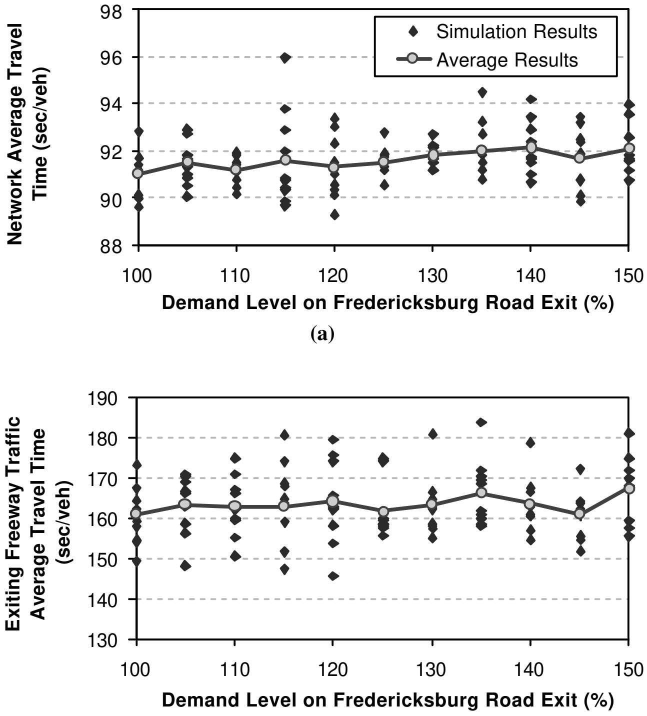
(d) (e)

FIGURE 3 Effect of train-crossing duration on (*a*) travel time, (*b*) fuel consumption, (*c*) HC emissions, (*d*) CO emissions, and (*e*) NO_x emissions.

not only the flows that would respond to traffic information displayed on VMS equipment but also vehicles traveling on the surrounding streets and arterials on which the diverted flows may choose to travel.

Figure 5 illustrates the results of simulations that were conducted to evaluate the potential benefits of using VMSs to preemptively warn motorists traveling on I-10 about traffic blockages at the Fredericksburg Road exit. These benefits are evaluated for scenarios considering a 6-min traffic blockage and various levels of driver response to the displayed messages. Similar to Figure 3, the diagrams shown in Figure 5 illustrate the impacts on travel time, fuel consumption, and emissions for both the total network traffic and the exiting freeway vehicles that travel between the O–D pairs of nodes 1-6, 1-11, and 1-12.

The top diagram of Figure 5 indicates that use of the VMS system has relatively little impact on travel times. For the exiting freeway traffic directly affected by the VMS system, slight but steady reductions in travel time are observed for increasing response levels of up to 40%. At a 40% response level, the average travel time for the affected freeway traffic is reduced by 2.1% when compared with a situation with no driver response to the VMS system. Past this level, the average travel time for the affected freeway traffic starts to increase again. At the 100% response level, a 1.2% increase in travel time is observed when compared with the scenario with no driver response. However, a statistical analysis through a paired student's *t*-test reveals that these changes are not statistically significant at the 90% level. This means that, while small differences are observed with the simulation results, it cannot be concluded that the use of the



(a)

(b)

FIGURE 4 Effects of traffic-demand level on (*a*) network average travel time and (*b*) exiting freeway traffic average travel time.

VMS system would definitively improve travel times for the exiting freeway traffic or the network traffic in general.

The above results can be explained by the changes in traffic equilibrium and traffic congestion that result from diverting traffic away from the Fredericksburg Road crossing. When only a small number of vehicles respond to the VMS system and adopt a diversion route, the ability for these vehicles to avoid being delayed for several minutes at the Fredericksburg Road crossing easily outweighs the added delays that result from the increased traffic congestion on the links that are on the diverted route. However, when too many vehicles divert, the added congestion caused by the increased traffic on the diversion route starts to outweigh the benefits of avoiding the closed railroad crossing. Also, as more vehicles divert, motorists at the railroad crossing experience less congestion, thus reducing the benefits of avoid the railroad crossing. In this case, an apparent optimal solution seems to be when no more than 40% of drivers respond to the VMS system.

However, contrary to the impacts on travel times, the remaining diagrams of Figure 5 indicate that increased responsiveness to warnings displayed on the VMS equipment translate into higher vehicle fuel consumption and emissions. For a 40% response level, the increase in average fuel consumption for the exiting freeway traffic affected by the VMS system would be 1.9%. The increase in HC, CO, and NO_x emissions would be 12.3%, 8.9%, and 2.0%, respectively. For a 100% response level, the increases reach 5.4% for fuel consumption, 26.1% for HC emissions, 18.9% for CO emissions, and 4.7% for NO_x emissions. At the network level, very little changes are observed, mostly due to the small number of diverting vehicles. From a statistical point of view, the changes in fuel consumption become statistically significant for levels of driver compliance at and above 50%, while changes in vehicle emissions are significant at any level of driver compliance. Similar trends were also observed for the scenarios considering exit demand levels that are increased by 25% and 50%. While trends similar to the travel-time results may have been expected, the results of Figure 5 can be explained by the fact that diverting vehicles from the freeway to urban signalized streets causes greater speed variability for the diverted vehicles, which results in turn in more vehicle fuel consumption and emissions for these vehicles. As such, these results clearly indicate that considering only delay reductions may not be sufficient to properly evaluate the benefits of VMS systems and that environmental impacts should thus be considered.

CONCLUSIONS

This paper investigated the potential of using VMSs to provide warning information to freeway motorists about railroad crossing closures near freeway exits. This investigation was carried out using the Fredericksburg Road crossing near Exit 567 on I-10 in San Antonio, Texas, as a case study, and the INTEGRATION simulation model as an evaluation tool. In the study, the impacts of train operations and VMS messaging on traffic-flow operations were evaluated by simulating scenarios with various train-crossing durations, levels of traffic demand on the Fredericksburg Road exit, and levels of vehicle response to the VMS system.

The analysis first outlined the significant impact of train operations on traffic-flow performance at the selected crossing. When compared with a scenario without closures, it was determined that the passage of an average 6-min train caused a 7.3% increase in total network travel time under existing traffic demands as well as some increases in fuel consumption and vehicle emissions. The analysis further indicated that increases in traffic demand on the I-10 Fredericksburg Road exit would not significantly affect network traffic performance.

In terms of traffic-flow performance, only marginal benefits were found from the use of the VMS system. In particular, small reductions in total travel times for the freeway traffic affected by the train operations at the Fredericksburg Road crossing were observed under driver compliance levels of up to 40%. These reductions also did not significantly reduce the total network travel time due to the small ratio of diverted vehicles with respect to the total network flow. Lesser benefits were also obtained with compliance levels exceeding 40% due to increased congestion on the diversion routes. This result particularly indicates the dependency that exists between the benefits that can be obtained from the use of advanced information systems and the levels of traffic congestion that exist on potential diversion routes.

In the final evaluation, the use of the VMS system to preemptively warn freeway motorists about traffic blockages at the Fredericksburg Road exit resulted in higher fuel consumption and vehicle emissions under all levels of driver compliance as a result of the increased speed variability along the arterial diversion routes. These results indicate the need to consider not only reductions in travel times when evaluating the potential benefits of VMS systems but also the fuel consumption and emissions impacts of these systems.

It is recommended that an evaluation of the safety impacts of the VMS system be conducted using crash-risk models.

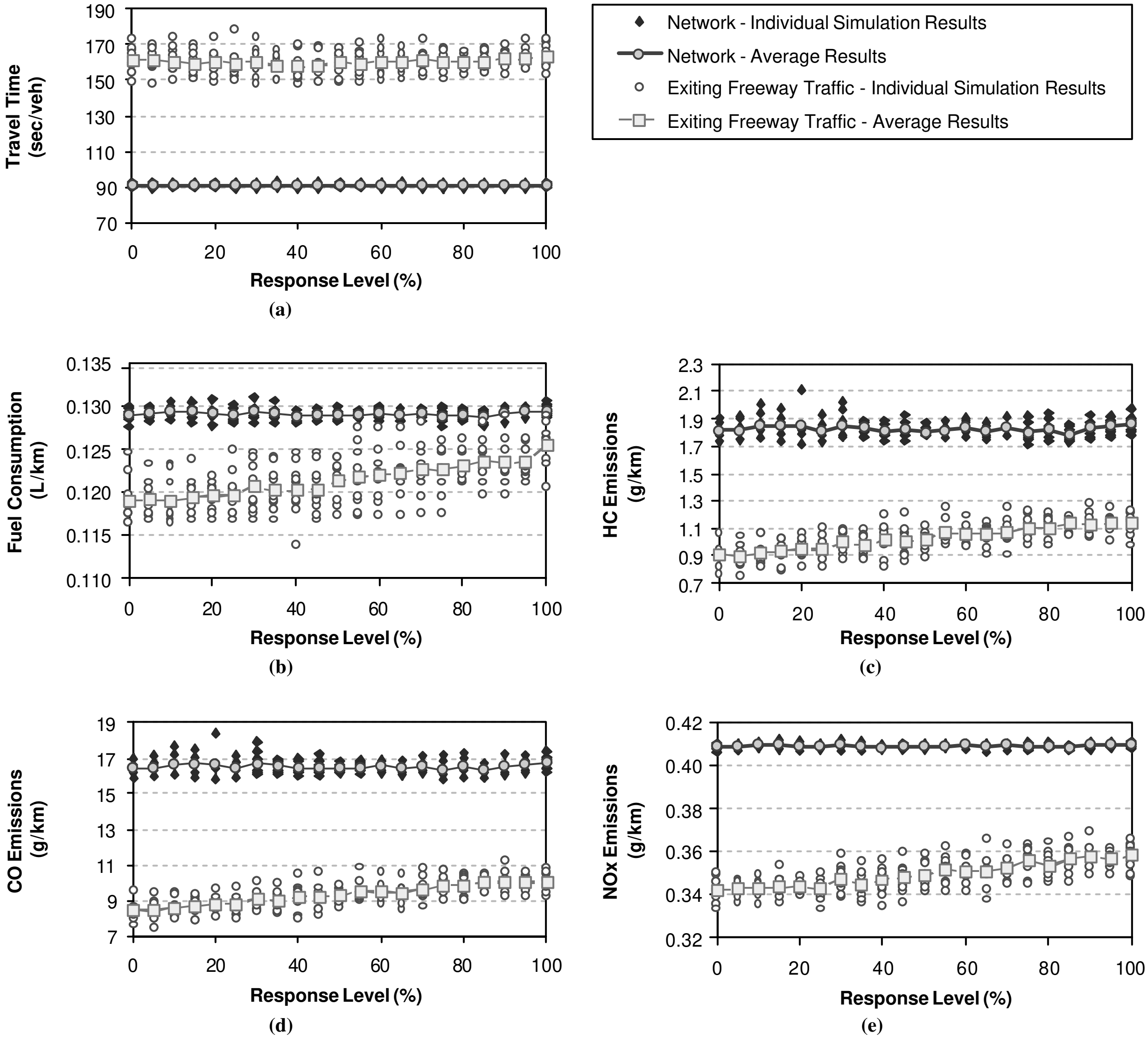


FIGURE 5 Effects of driver-response level on VMS system on (*a*) travel time, (*b*) fuel consumption, (*c*) HC emissions, (*d*) CO emissions, and (*e*) NO_x emissions.

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