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UNIVERSITY OF CALIFORNIA, BERKELEY

Estimating ATIS Benefits for the Smart Corridor

Raja Sengupta,
Bruce Hongola

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MOU 207 Final Report: Estimating ATIS Benefits for the Smart Corridor

Principal Researcher: Raja Sengupta
Analyst: Bruce Hongola

PATH - Institute of Transportation Studies
University of California, Berkeley

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ABSTRACT

This research investigates the effects on traffic in the Smart Corridor, i.e. the Santa Monica Freeway(I-10), using Advanced Traveler Information Systems (ATIS) for the management of congestion. It is believed that congestion can be mitigated by dynamic assignment of traffic from over-utilized to under-utilized roads. In this study, the assignment of traffic involves diversion to arterials from the Smart Corridor.

This project estimates the potential travel time savings of using ATIS for the diversion of traffic from the Smart corridor to arterial roads when non-recurrent congestion occurs. Most non-recurrent congestion on the freeway is caused by incidents. Consequently, there is considerable interest in finding ways to manage incident induced congestion on this freeway. The timely provision of incident information and diversion advice could alleviate non-recurrent congestion.

Simulation modeling of the Smart corridor is used to quantify the potential impact of various kinds of diversion advisories on corridor performance. The simulation model of the freeway may be described as a macroscopic model where vehicle movement is consistent with hydrodynamic theory. It should be noted that a strategy used to divert traffic in the simulation model corresponds to the availability of ATIS systems in a real world traffic situation. The times at which diversion starts and ends and the amount of traffic to be diverted are simulated but not the direct existence of ATIS devices(e.g. CMS). For example, traffic which is diverted immediately after an incident occurs in the simulation would imply that the drivers would have get the information to divert by some means.

The intent of the study is to establish relationships between traffic management variables(e.g. incident detection time, incident duration, capacity reduction, percentage of traffic diversion, and duration of traffic diversion). The focus was not to develop a high fidelity microscopic traffic model such as the ones used for planning purposes in some Caltrans districts(e.g. FHWA model CORSIM).

The questions addressed in this study are relevant since the corridor analyzed is a site used for Intelligent Transportation System demonstration projects. There is a cooperative agreement between local agencies and Caltrans to support the diversion of traffic during incidents from the freeway to arterial roads and back to the freeway if necessary. For the successful operation of this corridor it is important to understand the diversion levels that need to be achieved and also the effect of incident detection and clearing systems on the operation of the corridor.

Keywords: Smart Corridor, arterial, ATIS, ITS, CMS, FHWA, CORSIM(Corridor Simulation), dynamic traffic assignment, travel time, incident management, incident detection

EXECUTIVE SUMMARY

This study uses simulation modeling to estimate the potential travel time savings of using ATIS to divert traffic from the Smart Corridor to arterial roads when incidents occur. The timely provision of incident information and diversion advice to drivers could alleviate non-recurrent congestion. This study shows that if the goal is to reduce total travel time as much as possible, high percentages of traffic should be diverted when an incident occurs. The additional traffic can be handled by the excess capacity available on the arterials. Also, vehicle queues are significantly longer on the mainline as capacity decreases due to an incident. Queues dissipate slowly if diversion to arterials is not continued after the incident is cleared.

Strategies which allow additional diversion to continue after the incident clearance time instead of stopping diversion at this time yield more travel time savings than strategies which instead allow diversion to start earlier(at incident detection time). The amount of time that traffic diversion continues after incident clearance time can be much greater than the amount of time between incident detection time and the time that a queue reaches a previous off-ramp. Starting diversion at incident detection time assumes that all travelers are informed about the incident immediately. The greatest travel time improvement comes from strategies that start diversion at incident detection time and continue diversion after the incident clearance time.

The specified diversion percentage for additional vehicles to be diverted may be greater than the actual percentage of additional vehicles that are diverted. This is because the travel time on the arterials can become as large as the mainline travel time from an exit location and so no additional traffic would be diverted even with higher specified diversion percentages. The minimum travel time route is always chosen for vehicles even if a high percentage of additional traffic to be diverted is specified.

The amount of additional traffic to be diverted due to an incident is subject to additional off-ramp exit constraints, e.g. specified signal timings. If the higher diversion percentage levels imply that the signal policy would not accomodate the additional flow, then the higher diversion percentages of traffic can be deemed infeasible or traffic can be diverted at more than one off-ramp upstream from the incident. An alternative is to set the signal timings to accommodate additional flow if lower total travel times are

worthwhile and if the additional traffic on arterials is tolerable.

For transportation planning purposes the relationships between traffic management variables(e.g. incident detection time, incident duration, capacity reduction, percentage of traffic diversion, and duration of traffic diversion) are relevant. The ranges of possible parameter values correspond to the extent to which ATIS must be available to help to alleviate congestion and reduce total travel time in the Smart Corridor and the arterials.

The sensitivity analyses conducted indicate that ATIS holds promise as being the most significant measure in reducing travel delay resulting from freeway incidents.

Contents

1 Introduction

This document is the project report for CALTRANS PATH MOU 207.

Advanced Traveler Information Systems (ATIS) are an emerging class of Intelligent Transportation Systems that harness advances in computing and communication to provide new tools for the management of congestion. It is believed that, in many roadway networks, congestion can be mitigated by dynamic assignment of traffic from over to under utilized roads. Accordingly, the timely dissemination of accurate information that helps drivers find under utilized routes, is critical for the effectiveness of ATIS.

This project estimates the potential benefits of using Changeable Message Signs(CMS) for the management of non-recurrent congestion in the Smart corridor, i.e., a section of the Santa Monica freeway(I-10) and six parallel arterial roads(Exhibit 1) lying between the Harbor freeway (I-110) in the east and the San Diego freeway (I-405) in the west. In particular, data for the west to east direction is used for this study. This section of the Santa Monica freeway is one of the most heavily used in the country, carrying as much as 11,000 vph at certain times during the day.

Most non-recurrent congestion on the freeway is caused by incidents. Due to the very high freeway utilization the effect of lane closure is severe with queues developing rapidly, propagating for several miles, and taking a long time to clear. Consequently, there is considerable interest in finding ways to manage incident induced congestion on this freeway. Such interest is further strengthened by the physical presence of several arterial roads that are close and run parallel to this particular section of the Santa Monica freeway. Moderate utilization of some of these arterial roads suggests that the timely provision of incident information and diversion advice could alleviate non-recurrent congestion. It has been hoped that CMS advisories will positively impact the number of drivers diverting to parallel arterial roads, thus allowing queues to be reduced, their formation delayed, their dissipation speeded up, and travel time improved.

We use a relatively simple, easily calibrated, simulation model of the Smart Corridor to analyze these possibilities by quantifying the potential impact of various kinds of diversion advisories on corridor performance. The simulation model of the freeway may be described as a cell transmission model(Reference [4]). This is a first order spatially and temporally discretized kinematic wave model. The freeway is divided into several cells. Each is calibrated using the parameters of a fundamental diagram, i.e., free flow speed, jam density, and capacity. These parameters were obtained from [1]. Freeway demand data expressed as AM peak hour link flows is obtained from [3]. The freeway and its parallel arterial roads are assumed to emanate from one lumped origin node and terminate at a lumped destination node. For the diverted traffic volumes considered in this study, we believe that this does not introduce any significant errors. The modeling of the arterial roads is even simpler. Arterial capacity and speed estimates were obtained from [3]. The capacity available to accommodate diverted traffic is assumed to be the difference of capacity and demand. Speed is assumed to be constant at 40 mph until the available capacity is exceeded. Fortunately, in all cases the volume of diverted traffic does not exceed the available capacity. Arterial travel time is computed using the speed value and adding an allowance for traffic signal delays.

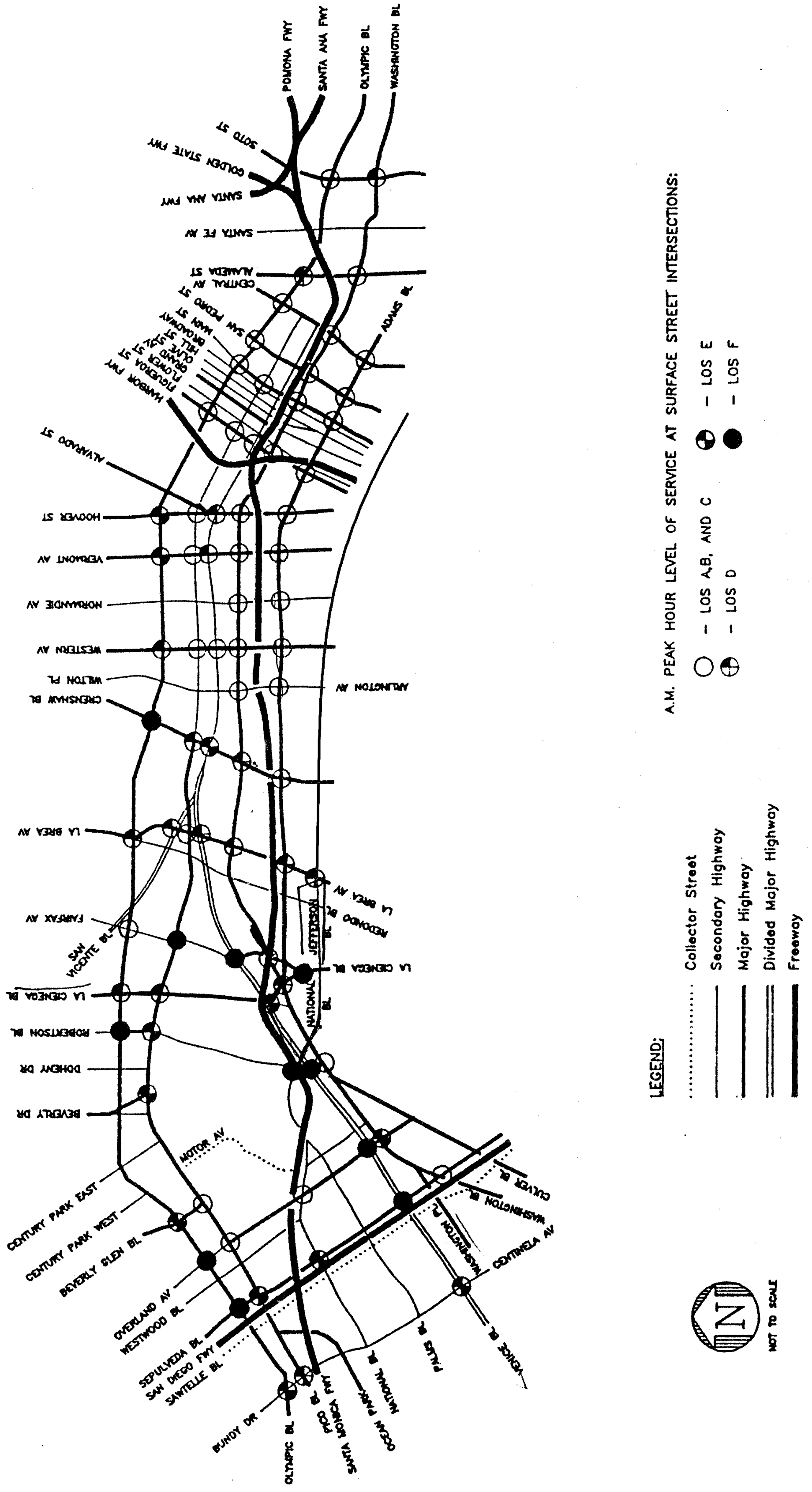
The analysis method is as follows. We simulate the occurrence of an incident. We have obtained data on the various kinds of incidents (location, duration, and number of lanes closed) that occurred in the Smart Corridor over a year of operation([5] [6]). Each type of incident is simulated. We record the total network travel time and the dynamic behavior of the freeway queue caused by the incident. It is useful to think of these two data items as the outputs of a simulation. The simulation inputs are the percentage of drivers diverting from the freeway to the arterial roads in response to dynamic information, the incident detection time, and incident clearing time. We have treated these three items as inputs because they are critical parameters that ITS technology can potentially improve. Thus we hope that the results documented in this report help transportation engineers working on the Smart Corridor understand the relative importance of these parameters, know the range of values at which they deliver benefits, and estimate the actual magnitude of benefits. The results also provide some insight into the dependence of benefits on incident location and the number of lanes closed due to the incident.

Each input parameter is studied over a range of values. We do this because for any given technology the value of these parameters is uncertain and can at best be represented by a range of values or richer statistical model. For example, the percentage of drivers diverting in response to an advisory may vary with the location of the CMS, its luminance, fonts, wording, the demographic profile of the Smart corridor driving population, and past experience with the advisories. The diversion percentages considered in this study are between 0 and 15 percent. Prior experience indicates that, in general, 15% of drivers tend to take alternate routes(divert) based on traffic reports[8]. These percentages are very common[1]. Similarly, incident detection often relies on the processing of noisy data which makes detection delay uncertain.

Since the credibility of the advisory information is very important, we model advisories as being provided only when the predicted travel time on the freeway exceeds that on the arterial routes. We are also concerned with the proximity(surrogate for visibility) of the physical queue during the use of diversion advisories. We analyze four diversion strategies that are increasingly conservative. Strategy 1 assumes that diversion advisories start only when the physical queue is proximate (within 0.1 mile) of the CMS location(near a previous off-ramp) and end as soon as the incident is cleared. This we believe is the most conservative and credible strategy, though, as our analyses show, it is the least effective. Strategy 2 assumes that diversion starts earlier, i.e. at incident detection time. This happens even if the queue has not reached the diversion point. Diversion ends at incident clearance time, as in Strategy 1. Strategy 3 continues diverting vehicles even after the incident has been cleared. Traffic diversion starts when the queue is proximate to the CMS location, as in Strategy 1. Finally, Strategy 4 assumes that diversion starts at incident detection time(as in Strategy 2) and continues beyond the incident clearance time(as in Strategy 3). This is the least conservative strategy, and our analysis shows that it is the most effective.

The structure of the report is as follows. Section 2 contains the description of the simulation model input and input sources. Section 3 describes the benefit/performance measures and diversion strategies. Sections 4 and 5 contain the study results and conclusions. Section 7 contains the software design description of the model.

Exhibit 1 - Santa Monica Smart Corridor



Freeway Subsection	Cell Numbers	Length(mi)	Incident Cells
up to La Cienega	41 - 50	.97	45
La Cienega - Fairfax	50 - 56	1.81	
Fairfax - La Brea	56 - 69		60
La Brea - Crenshaw	69 - 78	.97	74
Crenshaw - Western	78 - 93	1.52	85
Western - Normandie	93 - 99	.5	96
Normandie - Vermont	99 -105	.56	102
Vermont - Hoover	105 -110	.47	108

Table 1: Cell Location Data

2 Simulation Model of the I-10 Corridor

This section describes the baseline data used for all test cases. The differences between cases are in the choice of incident location, number of lanes blocked, and percentage of additional vehicles diverting at an off-ramp previous to the incident. The nominal incident clearance time is chosen to be 20 minutes.

The simulation time step dt is chosen to be .00275 hours. The time step is based on a constant speed of 40 mph to cover .11 miles, a typical cell length. The assumption of 40 mph comes from reference [1], page 56. It is assumed that all cells have 5 lanes and that the number of lanes blocked by the incident is either 1 or 2. This results in a capacity reduction of the incident cell of either 20% or 40%. The capacities of the other cells remain the same. It should be noted that these capacity reductions are only for the incident cell and may imply a larger overall capacity reduction. Having 1 or 2 lanes blocked at a location corresponds to a capacity reduction applied to one cell at a time.

2.1 Cell Location Data

Table 1 shows the cell numbers mapped to locations along the Santa Monica Corridor. Each chosen incident location is mapped to an incident cell ID.

2.2 Cell Capacity and Density

The maximum cell capacity of 12000 *vph* was chosen to be just large enough to meet the existing traffic demand in the mainline location with the most traffic demand under non-incident conditions. An equilibrium flow is established with no queues formed in the absence of an incident. This is done to simplify the simulations of incident congestion and to separate this from recurrent congestion. Also, the capacity is not so large as to prevent congestion when an incident is defined. The maximum number of vehicles per cell is also defined. It can also be referred to as the normalized density, i.e. it is the product of the jam density and the cell length. The jam density used comes from reference [1], page 45. The value assumed for jam density is 210 $veh/mile/lane$.

2.3 Incident Modeling

The incident start time ts is chosen to be 100, which is a time at which the simulation has achieved normal equilibrium flow, i.e. the simulation is at steady state. Throughout the duration of the incident the incident cell is set to a reduced capacity whose value is determined by the number of lanes blocked(1 or 2) for a particular case. The incident detection time td and clearance time tc are defined as a function of incident detection delay i and duration j, respectively. $i = 2$ minutes and $j = 20$ minutes.

$$td = ts + \frac{i/60}{dt}$$

$$tc = ts + \frac{j/60}{dt}$$

2.4 Arterial Modeling

In this section the available capacity of the arterials is described. The arterials serve as alternate routes for additional traffic to be diverted from the mainline. The idea is to ensure that no congestion results from additional traffic diversion; therefore the assumed(constant) values for arterial travel time to the destination remain valid.

It should be noted that these capacities are maximums, i.e. they would be smaller as a function of the signal timing used at intersections. Also, the simulation does not use arterial capacities to restrict flow onto the arterials from the mainline. Instead, the

Section (off-ramp to offramp)	Washington Bl. (existing) flow)	Adams Bl. (existing flow)	Remaining Additional Capacity
1-2	1095	980	5925
2-3	1145	980	5875
3-4	705	715	6580
4-5	960	830	6210
5-6	775	650	6575
6-Hoover	1005	460	6535

Table 2: Arterial Capacity Data

off-ramp capacity constraint is used for this purpose. It is described at the end of this section.

Assumptions about the arterial capacities were obtained from Exhibit 10 (the existing demand in both Washington and Adams Bl.) and Exhibit 3b (the number of lanes in Washington and Adams) from the JHK report[3]. Since only "major" arterials are assumed to be used (Reference [1], page 55), a capacity of 2000 vehicles per hour per lane is obtained. They also conform to the number of lanes given in the JHK report. Two-lane off-ramps are assumed. Chapter 5 of the HCM [2] supports this assumption.

For example, from La Cienega to La Brea(La Cienega is the first and La Brea the second off-ramp) there are 1095 veh/hr for Washington Bl. and 980 veh/hr for Adams Bl. Therefore, the available capacity for Washington Bl. is $2 \times 2000 - 1095 = 2905$. Washington Bl. has 2 lanes in the section.

Available capacity for Adams Bl. is $2 \times 2000 - 980 = 3020$ veh/hr.

So, the total additional capacity for this section is $2905 + 3020 = 5925$ veh/hr. The other results in Table 2 were obtained in a similar way.

Additional traffic to be diverted due to an incident is done at an off-ramp before the incident location and would not exceed any of the above capacities. The largest flow on the mainline is almost 12000 vehicles per hour and the maximum diversion percentage is 15%. Therefore, the off-ramp capacity is large enough to avoid mainline congestion at steady state. The off-ramp capacity is 10 veh/dt where dt is the simulation time step. This is approximately 3600 vph. It is determined with the assumption that each off-ramp

Location	Cell/ Off-Ramp	Nominal Diverted Flow(vph)	Off-Ramp Flows(vph) for Diversion Percentages				
			3	5	7	10	15
up to La Cienega	50	1654	1927	2109	2291	2564	3020
La Cienega - Fairfax							
Fairfax - La Brea	69	574	850	1034	1218	1495	1956
La Brea - Crenshaw	78	371	696	912	1128	1453	1994
Crenshaw - Western	93	200	545	776	1006	1352	1928
Western - Normandie	99	1131	1486	1723	1960	2315	2907
Normandie - Vermont	105	1425	1761	1985	2210	2546	3107
Vermont - Hoover							

Table 3: Off-Ramp Flow Data

has 2 lanes and the capacity is 2000 $veh/hr/lane$. The off-ramp capacity is set to be about 90% of the capacity of 2 lanes. This is done to ensure that traffic on the arterials is not congested; therefore constant free-flow travel times on the arterials can be assumed.

Tighter capacity constraints on the off-ramps were not imposed because this depends to a great extent on ramp layouts and signal timings. Table 3 shows the ramp flows for each diversion percentage for each off-ramp. These numbers should be put together with knowledge of the configuration of a particular ramp and some traffic signal optimization to determine whether or not the flow is feasible. This would determine which of the higher diversion percentages are infeasible and determine the signal timing requirements for the lower/feasible diversion percentages. In the absence of such an analysis the off-ramp flows can be considered requirements for each corresponding diversion percentage that the traffic system must accomodate.

For the sake of simplicity, Table 3 shows exit flows such that all traffic is diverted at one off-ramp upstream from the incident. Alternatively, traffic could be diverted at more than one upstream off-ramp instead so that less traffic is diverted at each off-ramp.

2.5 Traffic Diversion

The nominal diversion factors are used to achieve the desired nominal diverted flow. This flow represents traffic that always diverts from the mainline either with or without an

Off-ramps with exit cells	nominal diverted flow(vph)	nominal diversion factors	arterial TT to dest(min)	off-ramp cap(veh/dt)
50	1654	.168	8.76	10
69	574	.059	6.06	10
78	371	.033	4.55	10
93	200	.017	2.28	10
99	1131	.094	1.44	10
105	1425	.124	.72	10

Table 4: Nominal Diverted Flow Data

incident occuring. They are calibrated values, i.e. when they are multiplied by mainline cell occupancies during the simulation the desired nominal diverted flow is achieved. The test case used for this purpose is the case where no incident is defined and the simulation is at steady state.

The arterial travel times to the destination are based on a free flow speed of 40 mph and distance to the destination(Table 4).

The off-ramp capacities are based on assumptions from Chapter 5 of the HCM Manual[2]. 2-lane off-ramps can accomodate a maximum of 4000 vehicles per hour, but this is an overestimate. A correction factor of .9 is used to reduce the value. This is done to prevent congestion in the arterials. Since arterial travel time is assumed constant they should not be congested. The nominal diverted flows and travel times are given in Table 4.

When an incident occurs, additional diversion to a previous off-ramp is desired so that total travel time is minimized. Therefore, the total diverted traffic flow is the sum of the nominal diverted flow (Table 4) and additional diverted flows due to an incident. Similar to the case for nominal diverted flows, factors for additional diversion are used so that additional diverted flow is determined as a fixed percentage of the mainline flow at an off-ramp location previous to the incident. In other words, the total diverted flow is the mainline flow multiplied by the sum of the nominal and additional diversion factors. The factors used for additional diversion are 0, .03, .05, .07, .1 and .15.

Upstream(1st cell)	Demand(veh/hr)	Demand(veh/dt)
41	9105	25.04
On-ramp Cells		
51	1760	4.84
70	2185	6.01
79	1070	2.94
94	520	1.43
100	505	1.39
106	445	1.22

Table 5: Upstream/On-Ramp Flow Data

Off-Ramp Cells	Diverted Flow(veh/hr)	Diverted Flow(veh/dt)
50	1655	4.55
69	575	1.58
78	370	1.02
93	200	0.55
99	1130	3.11
105	1425	3.92

Table 6: Off-Ramp Flow Data

2.6 Demand Data

The demand data was evaluated applying Exhibit 11 given in the JHK Report [3]. Exhibit 11 was used because it gives the values for the morning peak hour. It was also standardized by the time step dt used in the simulation program, given by 0.00275 hours. Traffic demand is shown below in Table 5. The flow values for the off-ramps, i.e. the nominal flow of vehicles leaving the freeway, are shown in Table 6.

Level of Service is a ratio of demand to capacity. The maximum capacity of 12000 vehicles per hour was chosen so that LOS is almost 1.0. This is necessary to achieve a steady state simulation with no queues formed. This can also be done with a larger capacity, but the excess capacity(i.e. $LOS < 1.0$) may enable the simulation to avoid queue formation after the incident start time. The intent is to generate queues, i.e. to have congestion as a result of defining incidents. Level of service A represents excellent

LOS A	0.00-0.35
LOS B	0.35-0.54
LOS C	0.54-0.77
LOS D	0.77-0.93
LOS E	0.93-1.00
LOS F	1.00-1.25
LOS F(1)	1.25-1.35
LOS F(2)	1.35-1.45
LOS F(3)	1.45

Table 7: LOS Data

or free-flow conditions and LOS F represents overloaded conditions. The level of services that is given in Exhibit 21 of the JHK Report [3] shows that close to the sections of La Brea, Crenshaw and Vermont the LOS are F, E and F, respectively, for the AM peak hour. Table 7 shows the LOS values.

3 Experimental Design

3.1 Benefit/Performance Measures

The benefit measures for simulations use total travel time. Total travel time is the sum of the arterial and mainline travel times. For any given simulation, the miminum total travel time is found. If To is the travel time for a case with 0% diversion and if Ta is the travel time for the corresponding case with $a\%$ diversion then the benefit increase for cases with $a\%$ diversion can be described. In absolute terms of travel time improvement the benefit increase is $To - Ta$ and in terms of the percentage improvement in travel time it is $(To - Ta)/To$.

3.2 Diversion Strategies

The diversion strategies are defined below. Strategies differ with respect to how soon traffic diversion is begun after incident detection time. They also differ with respect to the time at which additional traffic diversion is terminated.

Strategy 1:

Diversion begins after incident detection time when the cell with an off-ramp which is closest to the incident becomes saturated, i.e. the incident queue has reached that cell. If an additional cell with an off-ramp becomes saturated, i.e. the queue spans two or more cells with off-ramps, then the cell furthest from the incident is where diversion occurs. Diversion ends and the incident cell is returned to normal capacity at incident clearance time.

Strategy 2:

Diversion begins at incident detection time. This implies that all drivers know about the incident immediately. Diversion occurs at the off-ramp previous to the incident. Diversion ends and the incident cell is returned to normal capacity at incident clearance time.

Strategy 3:

Same as strategy 1 except that diversion continues after the incident clearance time until the end of the simulation.

Strategy 4:

Same as strategy 2 except that diversion continues after the incident clearance time until the end of the simulation.

4 Simulation Results

First, a comparison between Diversion Strategies 1-4 is made and the strategy yielding the best results is selected(4). Then comparisons are made for cases where the incident clearance time is reduced from 20 to 15 and then 10 minutes. These cases are done for a particular incident location(cell 85). Then, results in travel time savings for various percentages of additional traffic diverted due to an incident are compared for all incident locations using the selected strategy.

Intuitively, Strategy 4 should yield the best results since diversion is allowed to start earlier, i.e. at incident detection time, and diversion is allowed to continue after incident clearance time. The graphs in this section use the data from Section 9.

4.1 Comparison of Diversion Strategies

Figures 1 and 2 show a comparison of travel time savings for each diversion strategy. The percentage gain in travel time benefit is greater for the cases with 2 lanes blocked(40% capacity reduction) compared to cases with one lane blocked(20% capacity reduction). Since the arterial travel time is shorter then the mainline travel time, increased diversion percentages result in increased travel time savings.

In the attempt to improve travel time savings benefits, Strategies 3-4 are significantly better than strategies 1-2 since diversion is allowed to continue after the incident clearance time. For strategies 1-2 additional diversion stops at the incident clearance time. Incident clearance time is 20 minutes after the incident detection time. Incident detection time is 2 minutes after the incident start time.

For diversion percentages larger than 10, greater improvement results from strategies 2 and 4 when compared to 1 and 3 since diversion starts at the incident detection time. For strategies 1 and 3 diversion does not start until a queue of traffic reaches an off-ramp previous to the incident location. This results in marginal improvement in travel time as the diversion percentage is increased as compared to the travel time improvements for strategies 2 and 4.

Figures 3 and 4 show maximum queue length for each diversion strategy. Maximum queue lengths are smaller for cases with higher diversion percentages, which goes along with smaller total travel times. For diversion strategies 1-3 the queue length stays constant at higher diversion percentages. This queue extends back to the on-ramp preceding the incident but no further. However, the number of time intervals that the queue remains at this maximum length decreases as the diversion percentage increases. For diversion strategy 4 the queue never reaches the previous off-ramp for the higher diversion percentages and continues to decrease. When 2 lanes are blocked instead of 1, the queue lengths are longer due to additional congestion.

Figures 5, 6, 7, and 8 show that even though the maximum queue length is the same for higher diversion percentages, the queue remains at the maximum for shorter periods of time. Figure 9 shows the length of queues over time for a case with 2 lanes blocked.

A steady state/equilibrium flow is regained during the simulation only in the cases where one lane is blocked and maximum diversion is being used for Diversion Strategy 4. The existence of a queue at the end of the simulation in all other cases implies that steady state has not been regained.

Strategies 3-4 represent larger improvement over Strategy 1 than Strategy 2 does for both the 1 and 2 lane cases. This means that continuing diversion beyond the incident clearance time is more significant than starting diversion earlier(at incident detection time). It should be noted that there are many more time intervals in the simulation after incident clearance time than there are between incident detection time and the time the queue reaches the 1st previous off-ramp. Diversion after incident clearance time is significant to consider since traffic remains congested long after incident clearance time.

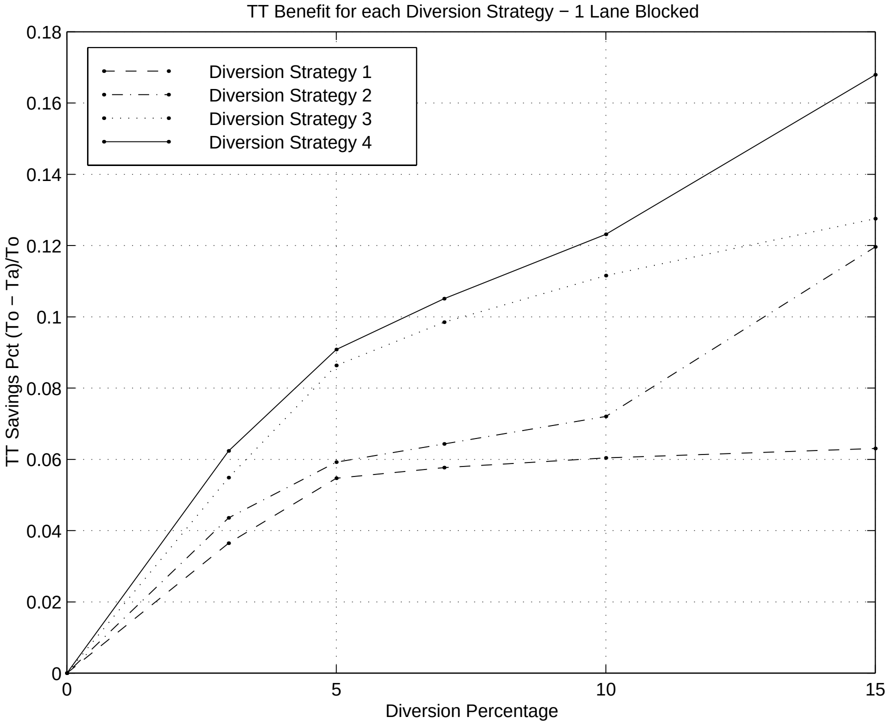


Figure 1: TT Savings for each Diversion Strategy - 1 Lane Blocked

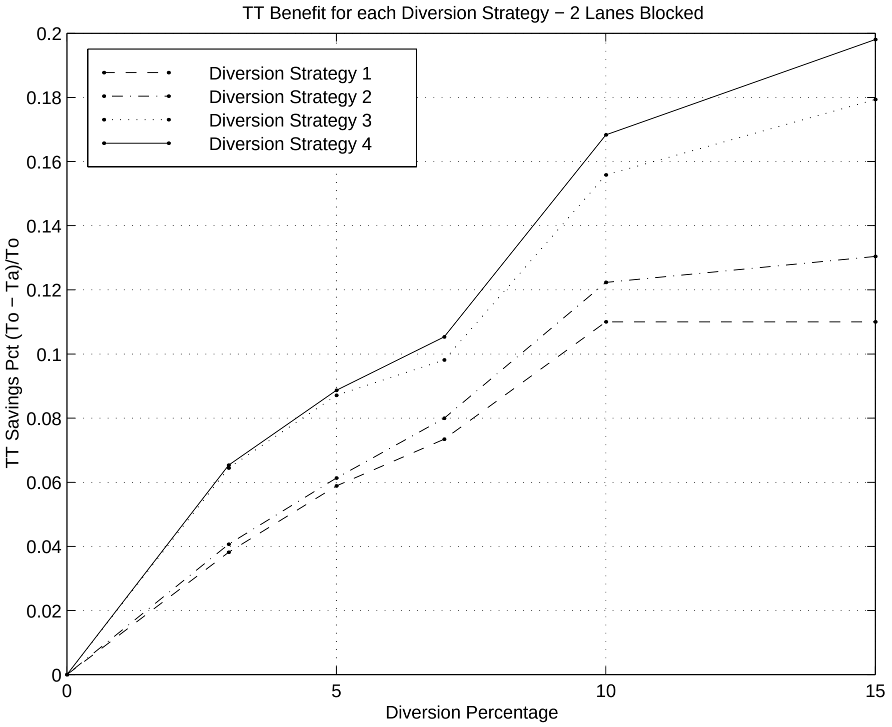


Figure 2: TT Savings for each Diversion Strategy - 2 Lanes Blocked

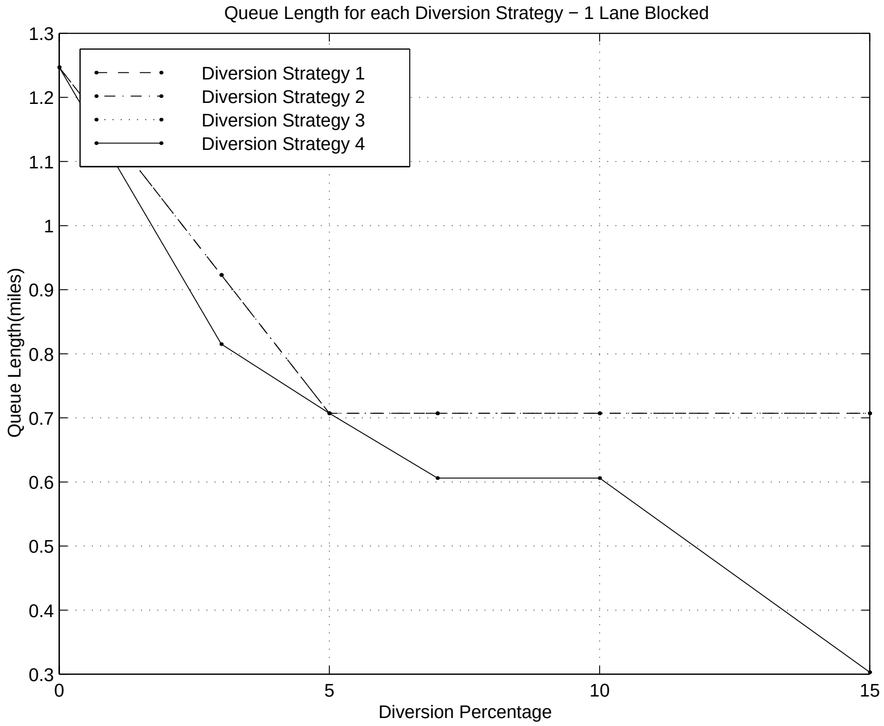


Figure 3: Queue Length for each Diversion Strategy - 1 Lane Blocked

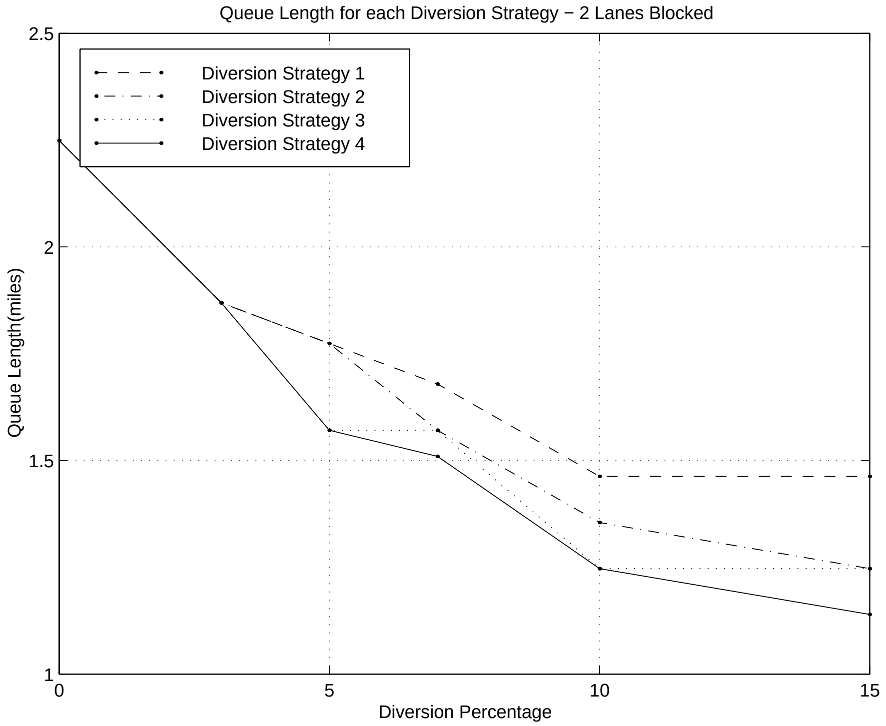


Figure 4: Queue Length for each Diversion Strategy - 2 Lanes Blocked

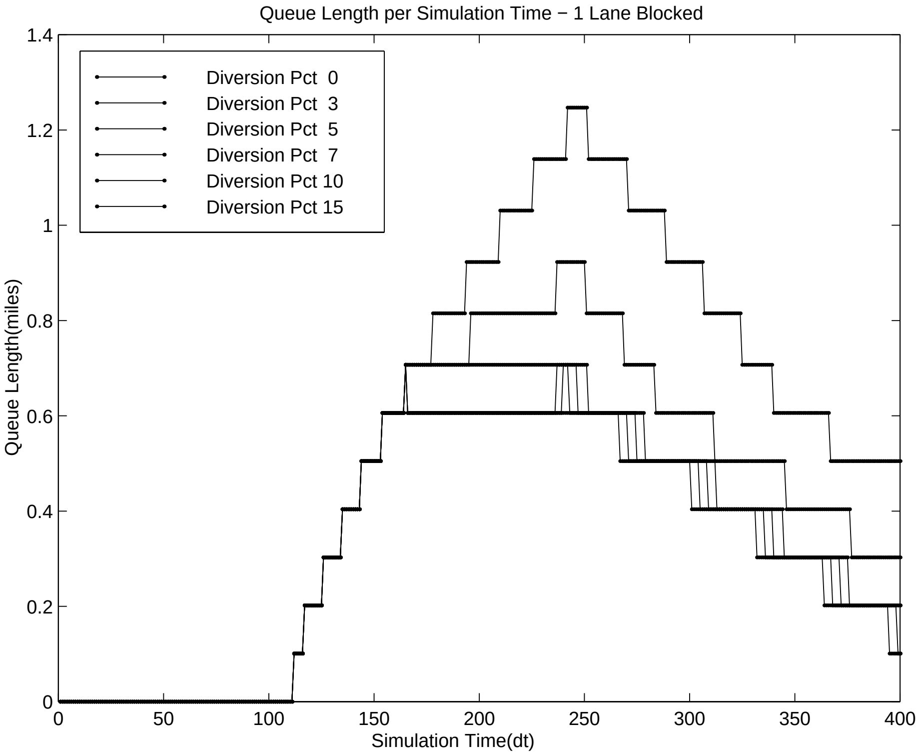


Figure 5: Queue Length for Diversion Strategy 1 - 1 Lane Blocked

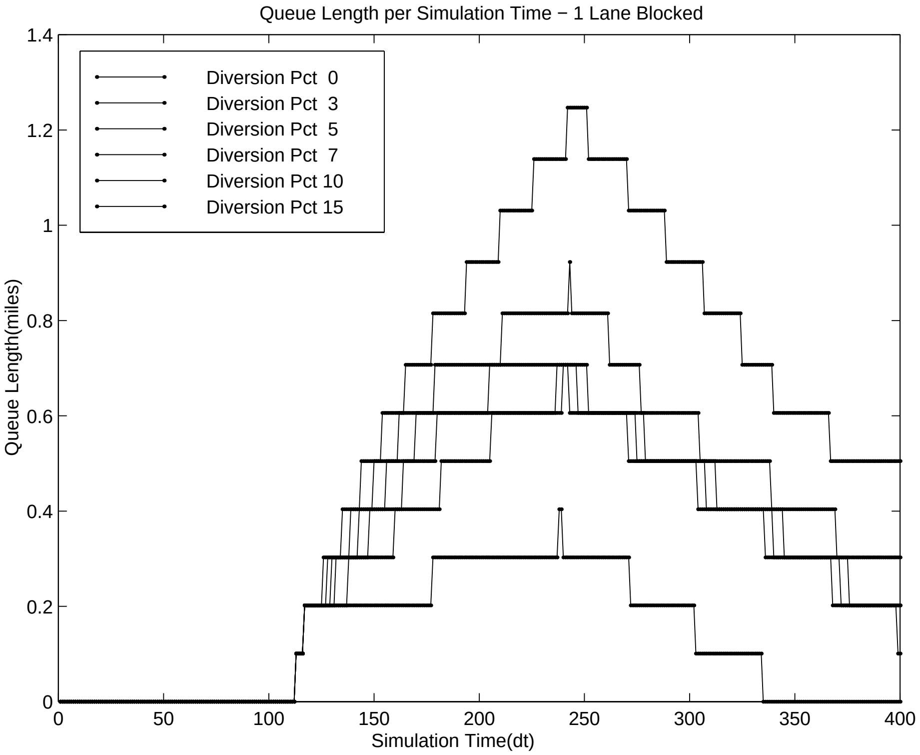


Figure 6: Queue Length for Diversion Strategy 2 - 1 Lane Blocked

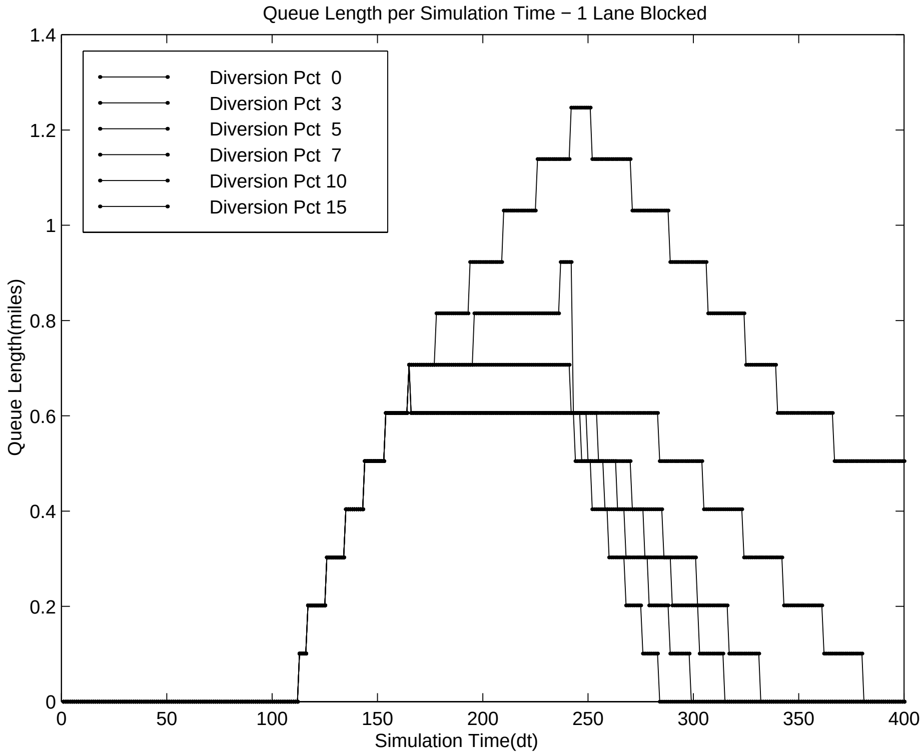


Figure 7: Queue Length for Diversion Strategy 3 - 1 Lane Blocked

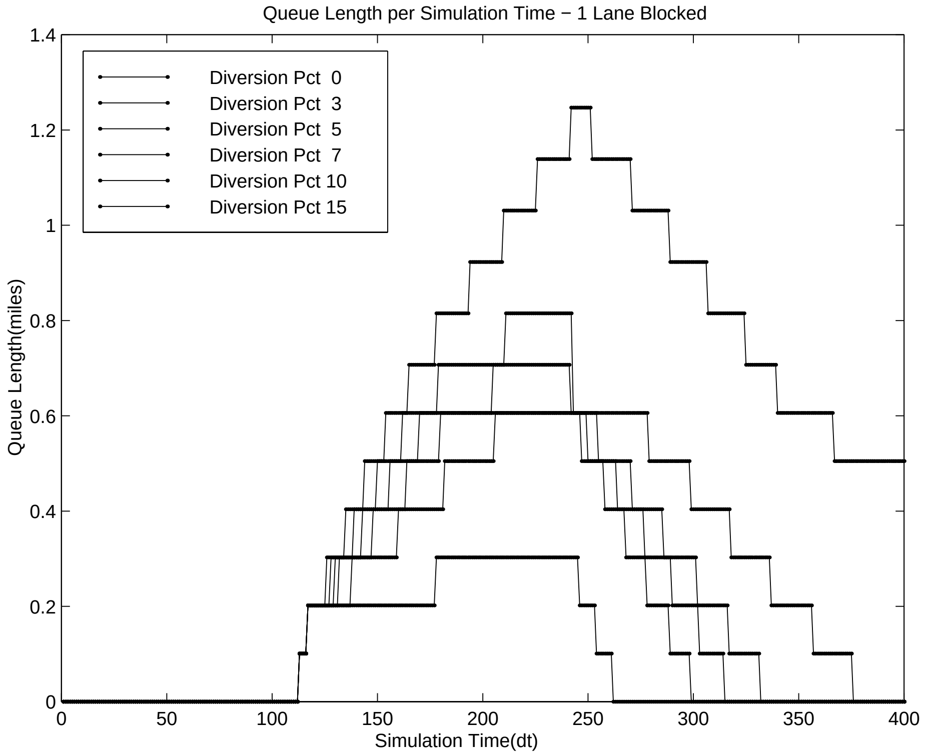


Figure 8: Queue Length for Diversion Strategy 4 - 1 Lane Blocked

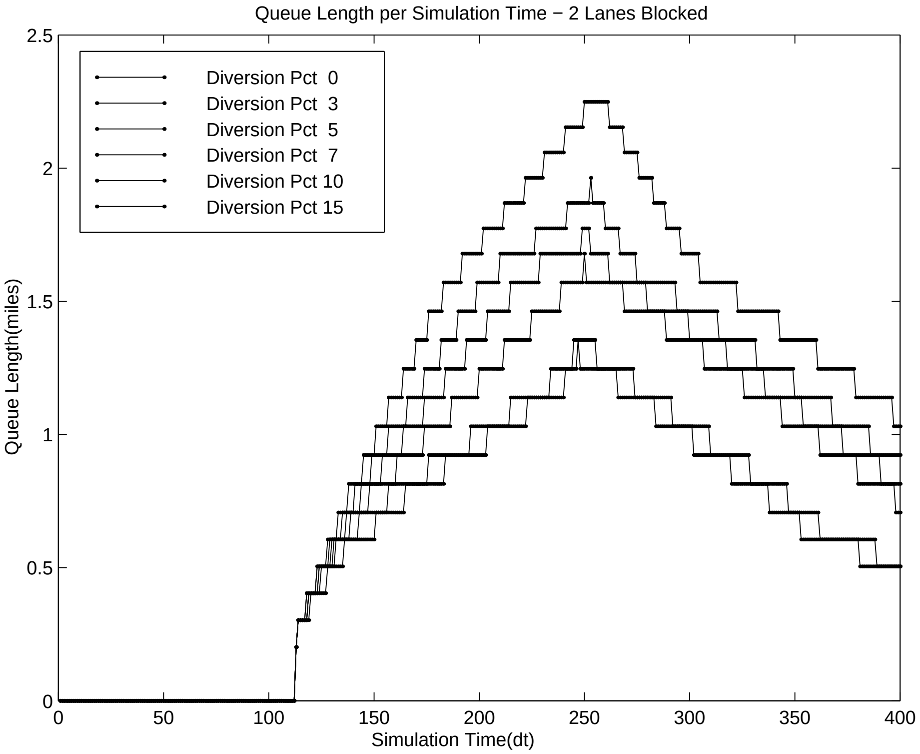


Figure 9: Queue Length for Diversion Strategy 2 - 2 Lanes Blocked

Diversion Strategy	Incident Dur(min)	TT(min) 1 Lane Bl	Pct Improve	TT(min) 2 Lanes Bl	Pct Improve
4	20	110516		126325	
4a	15	107344	3.0%	121234	4.2%
4b	10	104556	5.7%	116570	8.4%

Table 8: Incident Clearance Time Comparison

4.2 Comparison of Incident Clearance Times

Table 8 shows a comparison of travel time savings for different incident clearance times. These cases represent 0% additional traffic diversion. Travel times are in minutes. Diversion Strategies 4a and 4b are the same as Strategy 4 except that incident clearance time is 15 and 10 minutes, respectively. The total travel time decreases as the clearance time is decreased from 20 minutes. Also, the travel time reduction shows higher percentage improvements for the cases with 2 lanes blocked as compared to cases with 1 lane blocked. The percent improvement of travel time is calculated using the total travel time for the 0% diversion case for strategy 4. These improvements are not as significant as improvements due to high rates of diversion since the reduction in incident clearance time(i.e. the incident cell is restored to normal capacity more quickly) involves a smaller number of time intervals as compared to the length of time that diversion is occuring. However, reduction of the incident clearance time is another way to reduce total travel time with or without additional traffic diversion.

4.3 Diversion Strategy at each Incident Location

Figures 10 and 11 show the travel time savings at each incident location for each diversion strategy. Increased diversion percentages result in increased travel time savings at all incident locations. This happens because the arterial travel time is shorter than the mainline travel time.

The improvements in travel time are smaller for incidents near the end of the mainline since the traffic does not have far to travel if the incident is very close to the destination.

Travel time improvements for incidents close to the beginning of the mainline are

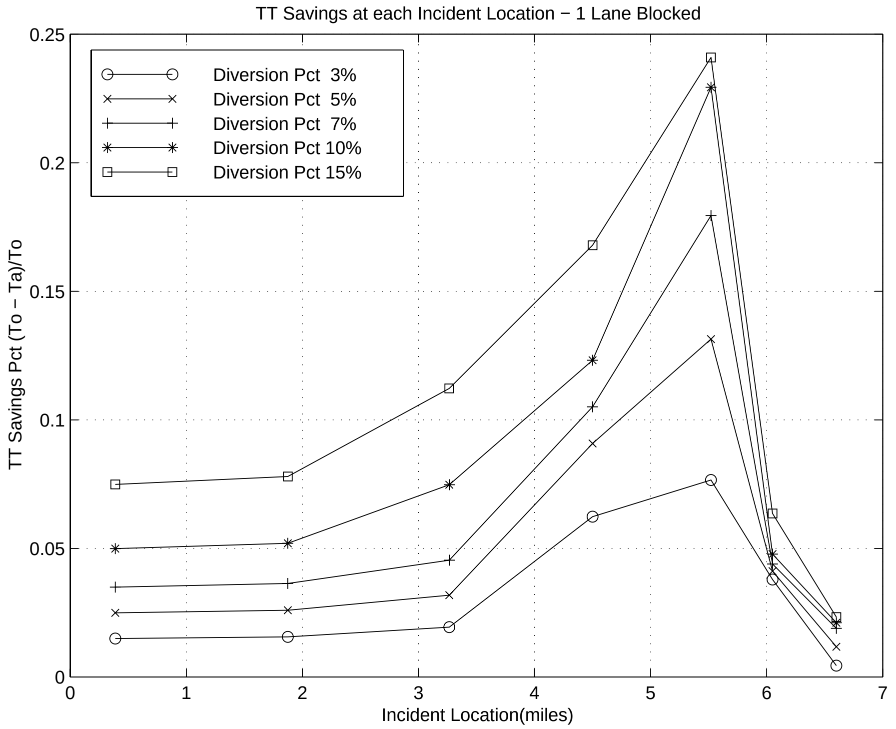


Figure 10: TT Savings for each Incident Location - 1 Lane Blocked

smaller since there is less traffic to divert. Demand is well below capacity at these locations so that congestion resulting from an incident is smaller and the travel time improvement is smaller.

The travel time improvements are greater when diversion is used for incidents that occur where the traffic flow is close to capacity. At these locations the travel time is the largest for the 0% diversion case when compared to the 0% cases for other incident locations. Figure 12 shows the mainline traffic flow for the steady-state case with no incident. As stated previously, the maximum capacity is just large enough to meet demand at the locations with the most traffic. Tables 5 and 6 were used to determine the mainline flow in Figure 12. Flow is decreased at locations with off-ramps and is increased at locations with on-ramps.

Figures 13 and 14 show maximum queue length for each incident location for all diversion percentages. Maximum queue lengths are smaller for cases with higher diversion percentages, which goes along with smaller total travel times. Also, queues are longer in

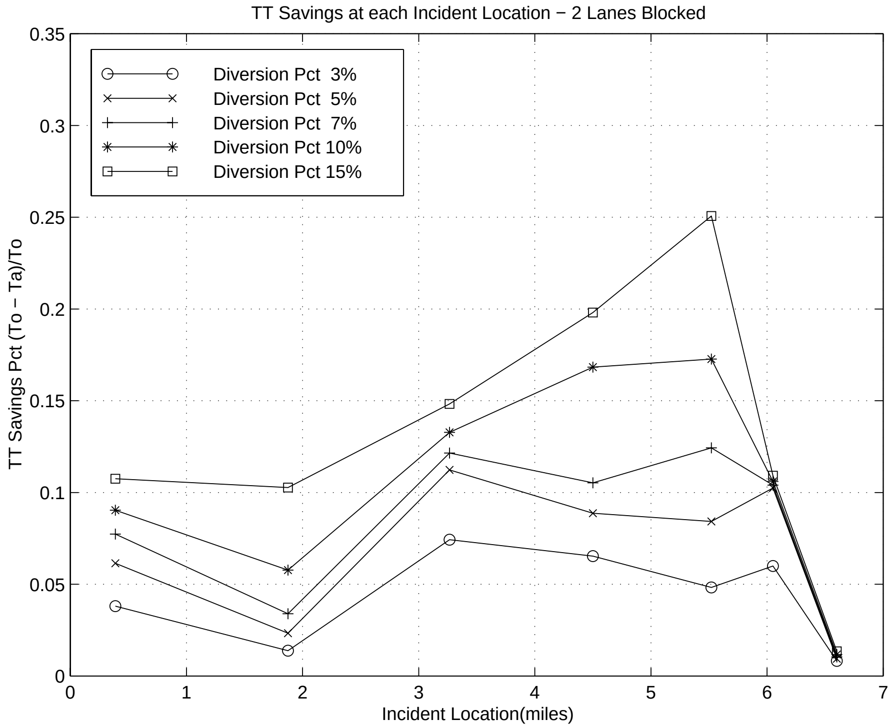


Figure 11: TT Savings for each Incident Location - 2 Lanes Blocked

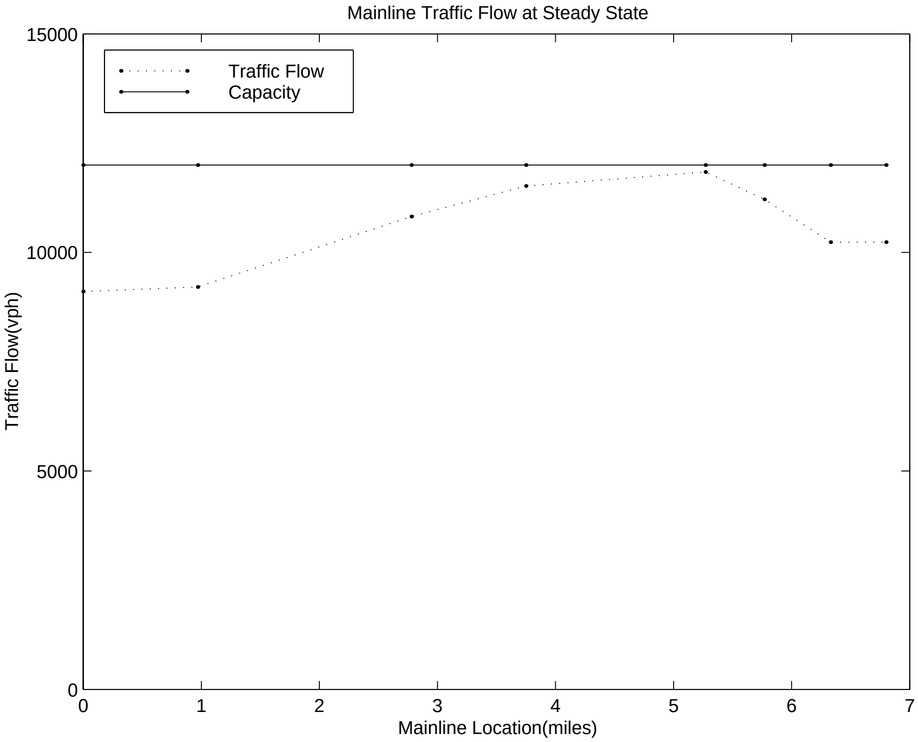


Figure 12: Traffic Flow - Mainline(vph)

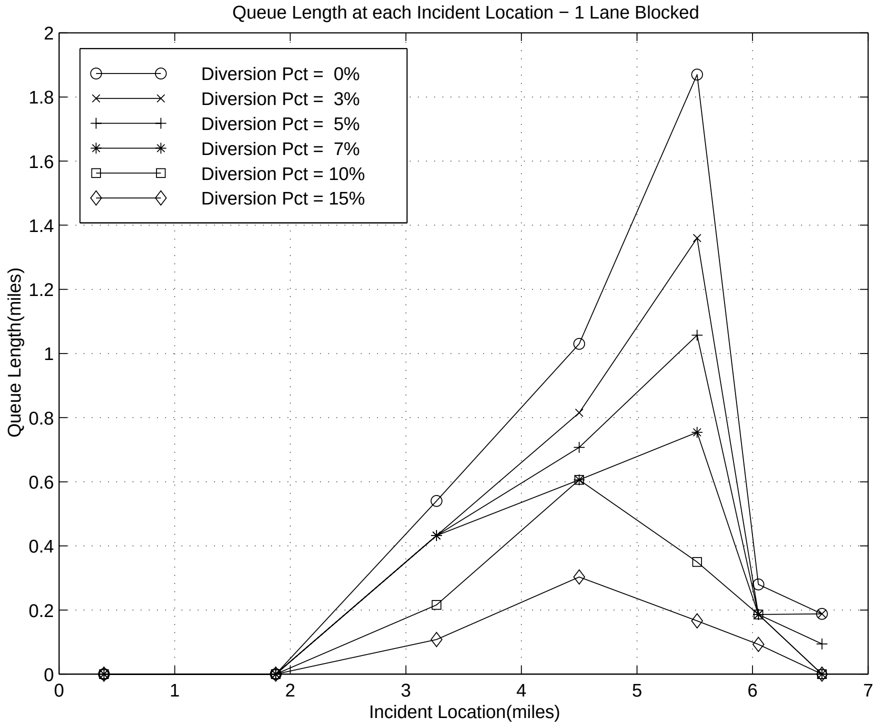


Figure 13: Queue Length for each Incident Location - 1 Lane Blocked

the cases with 2 lanes blocked as compared to the cases with 1 lane blocked. Queues are shorter when incidents are near the start of the mainline because there is less traffic to divert and flow is much less than capacity, as compared to other locations. Queues are shorter near the end of the mainline since traffic flow is less than flow at previous locations when flow is at steady-state with no incident defined.

Higher diversion percentages are needed to achieve higher travel time savings at the most congested locations when 2 lanes are blocked. When 1 lane is blocked, all diversion percentages yield higher travel time savings at the most congested locations.

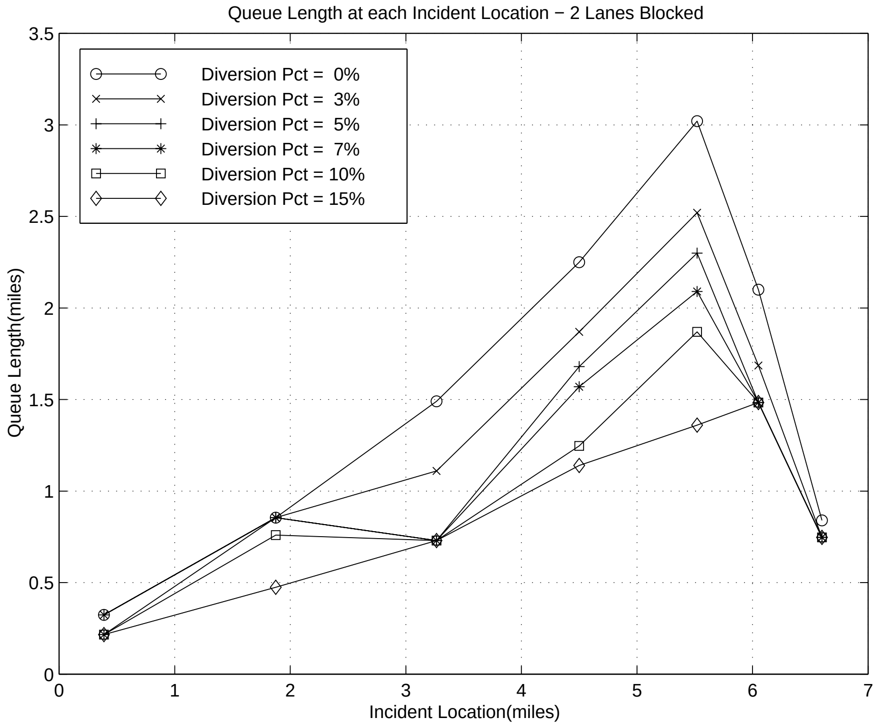


Figure 14: Queue Length for each Incident Location - 2 Lanes Blocked

5 Conclusions

These cases show that if the goal is to reduce total travel time as much as possible, the cases with the higher specified diversion percentages for additional traffic to be diverted should be used. However, this implies more traffic on the arterials leading to the destination. The additional traffic can be handled by the excess capacity available on the arterials, as described in Section 2.4. But since the travel time to the destination is modeled as a constant for all vehicles exiting the mainline, this can be an underestimate of the actual arterial travel time if a large number of vehicles are diverted. However, to mitigate this concern, the number of extra vehicles allowed on the arterials was not enough for the arterial road capacities to be reached. Also, vehicle queues are significantly longer on the mainline as capacity decreases due to an incident. Queues dissipate slowly if diversion to arterials is not continued after the incident is cleared.

Strategies which allow additional diversion to continue after the incident clearance time instead of stopping diversion at this time yield more travel time savings than strategies which instead allow diversion to start earlier(at incident detection time). The amount of time after incident clearance time is much greater than the amount of time between incident detection time and the time that a queue reaches a previous off-ramp. Starting diversion at incident detection time assumes that all travelers are informed about the incident immediately. The greatest travel time improvement comes from strategies that start diversion at incident detection time and continue diversion after the incident clearance time.

The diversion percentage for additional vehicles to be diverted may be greater than the actual percentage of additional vehicles that are diverted. This is because the travel time on the arterials can be as large as the mainline travel time from an exit location and so no additional traffic would be diverted even with higher specified diversion percentages. The minimum travel time route is always chosen for vehicles even if a high percentage of additional traffic to be diverted is specified.

The amount of additional traffic to be diverted due to an incident is subject to additional off-ramp exit constraints, e.g. specified signal timings. If the higher diversion percentage levels imply that the signal policy would not accomodate the additional flow, then the higher diversion percentages of traffic can be deemed infeasible or traffic can be diverted at more than one off-ramp upstream from the incident. An alternative is to set the signal timings to accomodate additional flow if lower total travel times are worthwhile.

The sensitivity analyses conducted indicate that ATIS holds promise as being the most significant measure in reducing travel delay resulting from freeway incidents. More detailed investigations should be conducted of the characterization of the key variables using high fidelity, i.e. more detailed corridor traffic models.

6 Acknowledgements

This study was funded by Caltran's New Technology and Research Program under MOU 207. The authors would like to acknowledge the helpful ideas of Reinaldo Garcia, Alexander Skabardonis, Pravin Varaiya, Y. B. Yim, and Wei-Hua Lin.

7 Simulator Design Description

The following is a description of a prototype software implementation of the Daganzo Cell Transmission Model [4]. The model includes incident detection, incident response, incident clearance and incident diversion. The program(SmartCor) consists of the following subfunctions:

- Data Initialization
- Demand Generation (for each time t)
- Cell Process (for each time t)
- Cell Process - mainline (for each time t)
- Cell Process - on-ramp (for each time t)
- Cell Process - off-ramp (for each time t)
- Arterial Process (for each time t)
- Incident Process (for each time t)
- Update Cell Occupancy (for each time t)
- Output Generation

7.1 Data Initialization

This function initializes the following data:

- Number of on-ramps
- Number of off-ramps
- Incident Cell ID
- Incident start time
- Incident detection time

- Incident clearance time
- Percentage of original capacity for incident cell
- Percentage of additional traffic to be diverted at previous off-ramp
- Percentage of traffic diverted in normal conditions at each off-ramp
- Identifier for each mainline cell
- Companion cell identifier for mainline cells with on-ramp or off-ramp
- Capacity for each cell
- Density for each cell
- Demand flow for upstream and for each on-ramp
- Arterial ID for each off-ramp
- Travel time for each arterial from off-ramp to destination

7.2 Demand Generation

This function generates the system demand flow for each on-ramp and for each time interval. Demand is a constant value for each time interval.

7.3 Cell Process

This function updates the state variables for each cell for each simulation time. The following variables are updated for each time step:

$yout_i$ flow from cell i that reaches downstream cell in the current time interval

$cell_i$ number of vehicles in cell i at start of time t

cap_k capacity of downstream cell k

den_k density of downstream cell k

$WAVE$ a multiplier($0 < WAVE \leq 1$) used to restrict flow to cell k

yin_k flow from previous cell i that reaches cell k at time t

Variables $yout_i$ and yin_i are used in function "Update Occupancy" to increase/decrease the value of $cell_i$ at each time step.

7.3.1 Cell Process - mainline

If the mainline cell has no on-ramp or off-ramp then the variables are updated as follows:

$$yout_i = min(cell_i, cap_k, WAVE \times (den_k - cell_k))$$

$$yin_k = yout_i$$

7.3.2 Cell Process - on-ramp

If the mainline cell has an on-ramp then the variables are updated as follows:

$$yin_m = demand_m$$

where m is the on-ramp identifier

If the mainline cell has an on-ramp, the variables are updated as follows:

$$yout_m = min(cell_m, cap_m, WAVE \times (den_k - cell_k))$$

$$yout_m = min(yout_m, cap_k)$$

$$yout_i = min(cell_i, cap_k - yout_m, WAVE \times (den_k - cell_k - yout_m))$$

$$yin_k = yout_m + yout_i$$

7.3.3 Cell Process - off-ramp

If the mainline cell has an off-ramp then the variables are updated as follows:

divnom Nominal pct of traffic to be diverted

divadd Additional pct of traffic to be diverted

div Total pct of traffic to be diverted

If additional traffic is to be diverted then $div = divnom + divadd$
if no additional traffic is to be diverted then $div = divnom$

$$yin_d = min(cell_i \times div, cap_d)$$

$$yout_d = yin_d$$

$$yout_i = min(cell_i - yin_d, cap_k, WAVE \times (den_k - cell_k))$$

$cell_i$ must be reduced along with $yout_i$.

$$cell_i = cell_i - yin_d$$

$$yin_k = yout_i$$

The Arterial Process Function is executed with $yout_d$ vehicles. These vehicles use the arterials to travel to the destination.

7.3.4 Arterial Process

If vehicles are exiting an off-ramp the travel time to the destination for this off-ramp is used to determine the arrival time at the destination for these vehicles.

$numveh$ Number of vehicles exiting at the off-ramp

$destcell_t$ Cumulative number of vehicles that arrived at destination

art_r Arterial ID for vehicles exiting ramp r

$ttart$ Travel time for vehicles using arterial art_r

$tottravel_t$ Total travel time for all vehicles

Update the number of vehicles arriving at the destination:

$$destcell_{t+ttart} = destcell_{t+ttart} + numveh$$

Update the total travel time after equilibrium is reached($t > 100$):

$$tottravel_t = tottravel_{t-1} + (numveh \times ttart)$$

7.3.5 Incident Process

This function computes the predicted travel time to the destination from each cell before the incident cell. If a mainline cell has an off-ramp then the arterial and mainline travel times are compared. If the arterial travel time is less than the mainline time, additional traffic is diverted to the arterials. Otherwise, only the nominal flow of traffic exits at the off-ramp.

$travelm$ Cumulative travel time on the mainline from a cell to the destination

$flowp$ Initial flow into incident cell at incident start time

$flowpon$ Predicted flow for cell with an on-ramp

$flowpoff$ Predicted flow for cell with an off-ramp

$demand_m$ Demand flow at on-ramp m

div_d Nominal diversion pct for off-ramp d

$divadd$ Additional diversion percentage

$ttart_d$ Arterial travel time for vehicles using off-ramp d

$queueln_t$ length of incident queue at time t

For each cell from the destination to the first cell the following is done:
Accumulate the predicted travel time $travelm$:
If $cell_i$ is downstream from the incident cell then $travelm = travelm + 1$
If $cell_i$ is upstream from the incident cell then the following is done:
Update the incident queue length $queueln_t$ as the number of cells in the queue
If $cell_i$ has no on-ramp or off-ramp then $travelm = travelm + (cell_i/flowp)$
If $cell_i$ has an on-ramp then $travelm = travelm + (cell_i/flowpon$
where $flowpon = flowp - demand_m$
If $cell_i$ has an off-ramp then $travelm = travelm + (cell_i/flowpoff$
where $flowpoff = flowp/(1 - div_d)$

If the cell has an off-ramp then $divadd$ is used to divert additional traffic if the travel time on the mainline is greater then the arterial travel time for vehicles leaving off-ramp d, i.e. if $travelm > ttart_d$

If $travelm <= ttart_d$ then $divadd = 0$

7.4 Update Cell Occupancy

This function updates the number of vehicles $cell_i$ as a function of variables yin and $yout$. The new values of $cell_i$ are applicable to the subsequent simulation time interval, i.e. $t+1$. Also, the total travel time $tottravel_t$ is updated for the mainline cells and the cumulative number of vehicles leaving each on-ramp is updated.

$acum_m$ = cumulative number of vehicles that have left on-ramp m

$vehtime$ = travel time for all vehicles in all mainline cells at time t

$tottravel_t$ Total travel time for all vehicles

The following is done for all mainline cells $cell_i$:

$$cell_i = cell_i + yin_i - yout_i$$

For each on-ramp m:

$$acum_m(t) = acum_m(t-1) + yin_m$$

yin_m was set using $demand_m$ for cells with an on-ramp.

If steady state has been reached then increment the total travel time using $vehtime$ where $vehtime$ is the sum of $cell_i$ for all mainstream cells i.

$$tottravel_t = tottravel_{t-1} + vehtime$$

7.5 Output Generation

This function produces the desired output for the following simulation variables:

a_t	cumulative number of vehicles that have left all on-ramps
$acum_{mt}$	cumulative number of vehicles that have left on-ramp m
$destcell_t$	cumulative number of vehicles that have arrived at the destination
$tottravel$	cumulative total travel time
$queueln_t$	length of incident queue at time t

For each on-ramp m, $a_t = a_t + acum_{mt}$ is done to accumulate the total number of vehicles leaving all on-ramps at time t.

For each simulation time t, arrays a_t, $acum_{mt}$, $destcell_t$, and $queueln_t$ are produced. Also, total travel time $tottravel$ is produced.

8 Possible Future Enhancements

This version of the cell transmission model generates constant demand for each of the on-ramps at the present time. An enhanced version could execute a function at each time period t that would stochastically determine the demand at time t. An appropriate probability distribution would be used where the mean of the distribution is the mean demand at each on-ramp. It may be desirable to use a pre-defined cumulative distribution function with all data points given also.

The model uses a constant travel time for the arterial(s) associated with each off-ramp. This implies that a constant link performance function for all links on an arterial is assumed. An enhanced version could determine the arterial travel times to the destination as a monotone increasing function of the number of vehicles that have departed the off-ramp. Since links can be on more than one arterial path to the destination, a dynamic traffic assignment problem must be solved. For this enhancement assumptions must be made about present and future travel times on the arterials at each simulation time step.

Reference [7] describes the functional capability of another implementation of the Daganzo Cell Transmission Model(Netcell). Aspects of the model described in this study can be considered for a future version of the Netcell Model, if desired.

9 Travel Time Data Tables

The following tables show the travel time data for the test cases. Table 9 shows the travel time for the 0% diversion case for each of the incident locations. Table 11 shows the travel times for the range of diversion percentages for each diversion strategy along with percentages of improvement in travel time. The graph data shown in the Simulation Results Section is based upon the data in these tables.

Table 9 is shown because it represents the worst case where no traffic is diverted as the result of an incident. In all other cases some traffic is diverted which results in improvement of the total travel time.

Each section of the Santa Monica Freeway has a number of accidents obtained by the TASAS data([5] and [6]). The percentage of cases where one or two lanes are blocked are assumed to be constant across all cases.

Benefits from test cases can be weighted as a function of the number of accidents/incidents at each location for evaluation purposes.

DS Diversion Strategy

4a tc = 15 min

4b tc = 10 min

b1 1 lane blocked in 80% of incidents

b2 2 lanes blocked in 20% of incidents

To Travel Time in minutes with 0% diversion

Ta Travel time with a% diversion - minutes

T Travel time with no incident - 94227 minutes

Incident Cell	b1	b2
45	94807	102390
60	94227	104263
74	101063	113282
85	110517	126325
96	119161	139534
102	100112	124499
108	96191	102327

Table 9: Travel Times with No Diversion

Diversion Strategy	Incident Location	Number of Accidents	TT Benefit Pct (To - Ta)/To a = 3 5 7 10 15		TT Benefit (To - Ta)		TT Benefit per accident
			b1	b2	b1	b2	.8b1 + .2b2
1	85	20	.04	.04	4030	4819	4188
			.05	.06	6046	7433	6323
			.06	.07	6377	9274	6956
			.06	.11	6678	13898	8122
			.06	.11	6968	13898	8354
2	85	20	.04	.04	4818	5138	4882
			.059	.061	6545	7744	6785
			.06	.08	7111	10102	7709
			.072	.122	7963	15453	9461
			.11	.13	13220	16477	13871
3	85	20	.05	.06	6063	8136	6477
			.086	.098	9542	11005	9834
			.098	.098	10885	12399	11187
			.111	.156	12332	19684	13803
			.127	.179	14096	22658	15808
4	85	20	.06	.05	6891	8254	6873
			.091	.078	10040	11203	10007
			.105	.105	11617	13303	11954
			.123	.168	13613	21263	15143
			.168	.198	18561	25021	19853
4a	85	20	.05	.04	5676	5313	5603
			.076	.067	8221	8151	8207
			.09	.11	9814	13831	10617
			.113	.17	12121	20559	13808
			.153	.197	16453	23865	17935
4b	85	20	.05	.06	4824	6896	5238
			.067	.09	6986	10907	7770
			.09	.13	8948	15243	10207
			.109	.167	11418	19432	13021
			.139	.192	14551	22337	16108

Table 10: Travel Time Improvements with Diversion

Diversion Strategy	Incident Location	Number of Accidents	TT Benefit Pct (To - Ta)/To a = 3 5 7 10 15		TT Benefit (To - Ta)		TT Benefit per accident
			b1	b2	b1	b2	.8b1 + .2b2
4	45	27	.017	.047	1656	4819	2288
			.029	.076	2760	7760	3760
			.04	.095	3863	9770	5045
			.058	.11	5519	11419	6699
			.087	.13	8279	13581	9339
4	60	90	.018	.016	1724	1752	1729
			.03	.03	2873	2956	2889
			.043	.04	4022	4293	4076
			.061	.07	5746	7292	6055
			.09	.124	8619	12981	9491
4	74	50	.02	.08	2144	9382	3591
			.0348	.125	3517	14192	5652
			.05	.135	5025	15352	7061
			.082	.148	8266	16776	9968
			.123	.165	12403	18733	13669
4	85	20	.06	.05	6891	8254	7163
			.091	.078	10040	11203	10272
			.105	.105	11617	13303	11954
			.123	.168	13613	21263	15143
			.168	.198	18561	25021	19853
4	96	7	.07	.044	8469	6096	7994
			.122	.076	14527	10642	13750
			.166	.076	19833	15704	19007
			.212	.156	25345	21818	24640
			.223	.227	26629	31669	27637
4	102	8	.04	.06	4191	7577	4868
			.045	.104	4551	12943	6230
			.049	.106	4862	13148	6519
			.053	.108	5283	13396	6906
			.07	.11	7033	13789	8384
4	108	6	.005	.01	491	1045	602
			.014	.012	1299	1195	1278
			.02	.013	2093	1321	1939
			.024	.015	2332	1485	2162
			.027	.017	2574	1710	2401

Table 11: Travel Time Improvements with Diversion

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