Simulating an evacuation event:

A test case involving the Diablo Canyon Power Plant
Simulating an evacuation event:
A test case involving the Diablo Canyon Power Plant

Micah L. Brachman
Richard L. Church
Carlos A. Baez

FiRST Project
GeoTrans Laboratory
Department of Geography
University of California, Santa Barbara
January 31, 2014

This report has been developed as a part of the First Responders System Testbed (FiRST) project at the University of California, Santa Barbara. The FiRST project investigates the integration of transportation and communication modeling and simulation to improve understanding and techniques of emergency preparedness and response. Please cite this report as: Brachman, ML, RL Church, and CA Baez (2013) “Simulating an evacuation event: a test case involving the Diablo Canyon Power Plant” (Report #01-2014-01), GeoTrans Laboratory, UCSB, Santa Barbara CA.
1. Introduction

Caltrans has two major transportation objectives: 1) improve public safety, and 2) reduce congestion and improve transportation efficiency. The typical focus is to improve daily operations of the state and federal highways within the context of safety and efficiency. However, it is also important to plan for unusual events, like floods, earthquakes, and tsunamis. Disasters are often accompanied by the need for evacuation. Recent evacuation events in California include the Station Fire (Altadena, La Canada, Sierra Madre, La Crescenta, etc.), the Jesusita Fire in Santa Barbara, and the Witch Fire in San Diego. These evacuation events can be time consuming and life threatening. Figure 1 shows traffic flow on Interstate 15, during a wildfire evacuation in San Diego County in 2007. An important objective in mitigating an evacuation event is to develop evacuation strategies that maximize effectiveness, minimize clearing times, and reduce risks. Modeling area-wide evacuation has been an important issue, since the development of evacuation plans for hurricanes and nuclear power plant disasters. In order to develop modeling techniques and to test possible evacuation scenarios, it is important to develop appropriate strategies for modeling and simulating traffic in an emergency. The Diablo Canyon Nuclear Power Plant was selected as a test case for evacuation modeling and planning. This test case is somewhat unique in that a “mock” contraflow plan had been developed. The basic premise was to use the Diablo Canyon Evacuation Plan (DCEP) as a starting point in which to compare and test strategies, evaluate modeling approaches, and focus on critical resource and personnel needs. It should be stated that traffic control in an evacuation event involving state and interstate highways is under the control of the California Highway Patrol (CHP). In the event that a DCEP is imposed, CHP would be in charge and Caltrans would be required to support their actions by providing appropriate levels of equipment and manpower. Supporting an event like a DCEP should not be undertaken lightly. In fact, the current plan itself appears to lack detailed instructions as well as estimates of clearing times. That is, current plans are not specifically geared to clearing the area as quickly as possible, as no comparison of strategies has been proposed or tested. Even though CHP is in charge of the operation, Caltrans does share responsibility for ensuring the plan and its possible execution utilizes the latest understanding and strategies. Figure 2 depicts the region surrounding the Diablo Canyon Power Plant. The largest center of population is the City of San Luis Obispo and the main traffic corridor is Highway 101, both shown in the red box in Figure 2.

One of the more notable evacuation events in the US involved hurricane Katrina and New Orleans. This evacuation operation was very successful for those who did not rely on public transportation and those who took the storm as a serious threat. Although most of the news about Katrina and New Orleans involved the stories of those who did not evacuate, the majority of people were able to evacuate from the region in a timely manner. The reason for the successful evacuation of the majority of the population of New Orleans was because of the implementation of a contraflow plan. A contraflow plan involves reversing traffic in a direction leading away from the event. For New Orleans, this involved reversing the west-bound traffic on I-10 East (which heads East from New Orleans), reversing East-bound traffic on I-10 West (which heads
west from New Orleans, reversing south-bound traffic on I-55 (heading North away from New Orleans), and reversing direction on several bridges (including one causeway across Lake Pontchartrain). This evacuation plan took considerable resources and personnel to set-up, operate, and decommission. However, the plan and its operation were considered important factors in the successful evacuation of hundreds of thousands of people. There are other elements of this evacuation event which will be discussed at the end of this report that could be addressed in future work.

Given that contraflow operations can help to increase the effective capacity in a specific direction, it makes sense to consider at least the possibility of using contraflow operations in California emergencies. In light of this, District 5 traffic engineers drafted a mock plan that involves a contraflow operation along the Highway 101 corridor in San Luis Obispo County. This mock plan demonstrates foresight on the part of Caltrans, as the use of “contraflow” operations may substantially reduce clearing times in a disaster. But, Caltrans and CHP lack the appropriate tools to test and compare the existing DCEP with the contraflow based DCEP or the information in which to support changing the existing DCEP to a contraflow-DCEP. Further, contraflow plans need considerable resources to set up and operate, and such resources may not

Figure 2: DCEP study area (red box), Diablo Canyon Power Plant location and surrounding cities

![Map of the DCEP study area, Diablo Canyon Power Plant, and surrounding cities.]

N

0 1 2 4 Miles

Morro Bay

San Luis Obispo

Baywood Los Osos

Diablo Canyon Power Plant

Pismo Beach
exist locally within the time frame needed to set up and operate such a plan. The first step is to propose and develop a mock plan. Subsequent steps must involve testing and comparing the contraflow plan with that of the existing plan. Such a test would involve the simulation of an evacuation event using both existing and new plans, and then using the results to help inform of possible modifications to either the existing plan or the contraflow plan. To test any plan requires a modeling approach which can help estimate clearing times and bottlenecks.

The next logical step would be to develop a simulation of the base case of DCEP and a simulation of the contraflow-based DCEP to help give guidance as to whether a plan change would be valuable. This is one of the objectives of the FiRST project, a collaboration between Caltrans and UCSB. The FiRST project has begun the development of a modeling framework for evacuation based upon the use of optimization and simulation modeling techniques. This report describes the use of a micro-scale traffic simulation model in testing the efficacy of the contraflow based DCE plan drafted by Caltrans engineers and discusses issues that are problematic in simulating such events.

There are a number of techniques that can be used to model the efficacy of an evacuation plan. They involve:

- Simple flow assignment models, where demand are assigned to their shortest route in evacuating an area. Such approaches can involve simple congestion factors, so that as traffic is routed on the network, each subsequent assignment can be based upon the shortest time available route. Such a model is considered ad-hoc as the assignment of demand to routes is based upon an order that may not occur. This approach often requires the fewest resources to accomplish, but is also the most unreliable.

- Optimal flow models solved using linear programming. Such models have been developed for building evacuation and small area evacuation. This approach is useful to develop a lower bound estimate on actual clearing times. It is also useful in identifying potential bottlenecks in traffic flow. The main benefit of this approach is that the data necessary to model and support a given problem is less than what is necessary in a micro-scale simulation model. An example of this approach has been developed as a part of this project, but will be presented in a different report.

- Simulate an evacuation event using a traffic simulation model. Traffic simulation models, like PARAMICS, VISSIM, and MATSim, can be used to simulate an event. Each of these three software systems are designed with a different underlying set of rules and scale. For example, PARAMICS is based upon a map database that represents real road geometry. Vehicle speeds are in part controlled by the curvature of the roadway, sightlines, and discontinuities in direction. VISSIM, on the other hand, is insensitive to any geometry of the map shape file and uses speed limits and other parameters entered by the user to control vehicle speeds. Both systems use an OD matrix of traffic demands and car following equations. MATSim, uses a different design basis. First, like VISSIM road geometry is not important. But unlike VISSIM and PARAMICS, MATSim uses a trip diary for each traveler. The traffic is the sum of the individual trips being made. Whereas, MATSim can model trip making behavior, PARAMICS and VISSIM model traffic for a given set of demand represented by an OD matrix. In addition, MATSim models traffic along a road segment based upon a congestion function. This is used to estimate how much time a given vehicle will spend on a link, without modeling individual car jostling.
along the link. Consequently, MATSim can model events much faster than the other two systems.

Thus, there are pros and cons for each of these systems, where one may be ideal for one task and another may be better for another. In this paper, we report on the use of VISSIM.

2. Data base development

In simulating an event, it is important to capture all elements that will significantly impact the functions being modeled or estimated. As a starting data base, we acquired NAVTEQ map tiles from PTV Corporation that covered the San Luis Obispo and Santa Barbara Counties. The main feature being modeled is the performance of Highway 101, using either the contraflow plan or Highway 101 without controls (there is a general split of traffic heading north and traffic heading south, and these splits are based upon the general evacuation plan). We developed a second form of the NAVTEQ network data by modifying it to match road closures, lane reversals, and route modifications as specified in the “mock” contraflow plan. The NAVTEQ data base contains center line information for road ways, lane data, and other attribute data, including the designation of a street being one-way and turn restrictions. Speed limits are not often given. It is important that all speed limits and assumed travel speeds be specified as well in the network. It is also important to capture multi-lane layouts accurately, turn lanes, and other elements. This data preparation can take a considerable amount of time to set up. In fact, setting up a data base for micro-scale traffic simulation is a time consuming and detailed task. For, VISSIM, it is absolutely necessary to have an accurate depiction of the network with respect to the attributes but not necessarily with respect to the road geometry.

As exact road geometry is not necessary for the simulation per se, one can be somewhat frugal in the time spent in generating an exact geometry as long as the attributes (like speed limits) are accurate. An example of this can be seen in Figure 3. Figure 3 depicts a short portion of Highway 101 and surrounding roads. You will note that the road segments are depicted as straight line segments drawn in blue. Logical connections are colored with magenta. Logical connections depict ramps and turn restrictions. This helps to aid in the use of the database in terms of navigation, supporting the common directions of “turn left” here and “take off ramp on right.” Note that the road network data (in blue) does not always have a connected set of lines (i.e. streets). The magenta lines represent turn and route restrictions, and without some of these restrictions, the network may not be completely connected. It should also be noted here that the network does not contain many shape points. Shape points are used in line representation to depict curves in roads. But, shape points are added features that expand the size of the data base. If one wants to use a database for navigation purposes, exact geometry with significant positional accuracy is not necessary. Consequently, a database can be reduced in size by keeping the use of shape points to a minimum, while still retaining enough data in which to provide navigational capabilities. Also note in Figure 3, that the lanes of the segment of Highway 101 in the figure are not depicted. The short portion of Highway 101 is depicted as two parallel lines, one representing the South-bound lanes and the other representing the North-bound lanes. Thus, the position and number of lanes are not depicted on the map (the number of lanes, however, is
included as an attribute). This is another element that may or not be resolved in the development of a traffic simulation model.

Figure 3: An example of road data layout from NAVTEQ where Highway 101 traverses from the center bottom to the top right corner of the image. The alignment of 101 is depicted with two parallel lines, depicting the South-bound and North-bound lanes. Each roadway is depicted with a line associated with a given direction of travel.

To understand this from a graphical perspective, roughly the same section of the map in Figure 3 has been resized and projected using an aerial photo as the background in Figure 4. Each roadway segment in Figures 3 and 4 is depicted with a line associated with a given direction of travel. For example, there is a somewhat vertical line segment at the bottom right corner of Figure 3 which abruptly turns left. This segment is depicted with one line segment, indicating that there is only one direction of travel. This same roadway can be found toward the center of Figure 4, where it can be seen that this line represents an off ramp for Highway 101. Note that this captures a given travel function, but does not accurately depict the roadway as it does not coincide with the image. In fact, this is not an unusual occurrence. In Figure 4, it can be seen that many of the road segments do not coincide with the image. Although the section of Highway 101 is represented by parallel lines with a reasonable level of accuracy, the major road crossing Highway 101 at the interchange is depicted with dual lines that coincide with only one direction of the separated roadway. Also observe that the intersection at the top center of the image in Figure 4 captures connectivity, but represents the roads connected to the intersection with less than what most would be considered reasonable from a graphical perspective. There are methods to automatically generate road curvatures from navigational databases, e.g. S2P, but such techniques cannot be relied upon to eliminate all issues in road representation.

One of the reasons why road depiction is discussed here is that micro-scale simulations greatest asset is the ability to depict vehicle movement along roadways in a realistic image. Such “moving pictures” of traffic help to visualize a given traffic event. The more an image departs
Figure 4: A portion of the road network depicted in Figure 3 superimposed on an air photo. Note the depiction of off ramps and on ramps of Highway 101 in the center of the image. Note, there is a railroad track that crosses 101 and is parallel to the roadway at the interchange.

from reality, the more one questions whether the simulation has adequately captured the movement of vehicles along a road segment. For example, if one simulated traffic along the road network in Figure 3 on the off ramp using the left angled roadway at the bottom left in the image, a vehicle would be depicted as taking the “corner” in the ramp at 20 miles per hour, without stopping! This behavior would quickly come into question by expert and layperson alike. Therefore, when depicting any event, including an evacuation scenario, one must generate a reasonable facsimile of the road system that superimposes well over an aerial photograph.

Figure 5 depicts the same image and road system after it has been edited. Editing such a network is time consuming and tedious work. This process is necessary if one intends to show any simulation movies on top of images. Consequently, using micro-scale traffic simulators with real images triggers the need for significant network editing. Such editing may be justified when a model is to be used on a frequent basis, in traffic operations and planning, but may not be justified when modeling a one-time event.

3. Estimating evacuation demand

There are a number of elements that make the simulation of an event like an emergency evacuation difficult to accomplish with any reasonable level of accuracy. One of these elements is the estimation of the demand for evacuation as well as the time frame in which this demand is
exerted. What makes this a complicated exercise is the lack of information concerning whether an individual will attempt to first return to the area to pick someone up, like an elderly person or a “latchkey” child. Also complicating the estimate is not knowing daytime and night time populations of neighborhoods. Often one assumes that an average number of vehicles will depart per household in each neighborhood. Although this may be somewhat realistic, based upon average vehicle ownership in a neighborhood, such an estimate must be made given the lack of specific information about individual behavior during an event. For the exercise reported here, we estimated demand for evacuation to be one vehicle per household. The total number of households was identified for each census block. Each block was represented by a centroid and the total demand for that census block was assigned to the centroid point. The nearest road segment to the centroid point based upon Euclidean distance was identified. These locations became inputs for traffic during the event.

It is important to note that the evacuation scenarios modeled here do not make any assumptions with respect to school children. For example, in a daytime emergency it would be expected that many parents would want to retrieve their children by going to their schools and picking them up. In the Diablo Canyon Evacuation Plan children are to be bused to special pick up points, e.g. a school in Santa Maria in the event of a mandatory evacuation. If parents do not understand all of the elements of such a plan, there may be a reverse flow in traffic that is generated by parents making needless trips and needless confusion.
Another major element that needs to be estimated is the distribution of departures from a neighborhood. For example, is there an immediate onslaught of traffic generated by people attempting to flee in a panic, or is there a more organized and deliberate demand in evacuating over a longer time period? For the estimates here, we assumed that demand for evacuation was exerted randomly over a two hour period. Data exists for evacuation demand and its distribution for events such as hurricanes. In an event such as a hurricane, inhabitants often have a warning which may be hours if not days ahead of the possible disaster. But, for an event such as a nuclear power plant disaster, the distribution of demand over time is unpredictable. For example, in the recent case in Japan, the tsunami caused significant damage to all infrastructure including a nuclear power plant. In some cases, evacuations were not immediate, but took days and even weeks to accomplish. Whatever the case, it is clear that inhabitants need clear concise information and guidance. It should be noted that shorter evacuation time periods for the DCEP results in grid lock.

4. Simulation results for a non-contraflow evacuation plan

We used VISSIM from PTV Corporation to model traffic flow on the network. To generate information about traffic flow, we placed VISSIM data collectors on each entrance ramp in the contraflow section of Route 101. Additional data collector sets were defined:

Data Collector set 1: this totals flow per time period leaving the network, having travelled either south or north on U.S. Highway 101 to a designated point outside of the evacuation zone.

Data Collector set 2: this totals North-bound flow per unit time period on U.S. Highway 101, having reached Atascadero and a designated point outside of the evacuation zone.

Data Collector set 3: this totals South-bound flow per unit time period on U.S. Highway 101, having reached Avila Beach and a designated point outside of the evacuation zone.

Data Collector set 4: this totals North-bound flow per unit time period on U.S. Highway 101, having reached the Highway 58 junction north of Cuesta Grade.

Data Collector set 5: this totals North-bound flow per unit time period on U.S. Highway 101, just north of the last 101 entrance ramp at Monterey Street.

Data Collector set 6: this totals vehicles per unit time period having entering U.S. Highway 101, North-bound or South-bound

In addition to vehicle flow data, these collectors also captured vehicle speeds [mph] (maximum, minimum and average) and queue delay times [seconds] (maximum, minimum, and average). We also collected data on system wide information like latent demand, average speed and delays. The position of the non-ramp data collector points are given in Figure 6. Figure 6 depicts the evacuation region, major roads, and the population density of the region that is outlined in Figure 2. One can easily observe from Figure 2 that the majority of the population in the area being
modeled resides in or near San Luis Obispo. Although there are communities north of Diablo Canyon Nuclear power plant that are along the coast (e.g. Morro Bay and Los Osos), these communities are supposed to evacuate by heading north along State Route 1 and Northeast along State Route 46 thereby circumventing the use of Highway 101. We assumed that this would be
the predominating flow pattern here, and because of this we did not include the north coast communities like Morro Bay and Los Osos. In addition, some eastern portions of San Luis Obispo are assumed to evacuate on State Route 1 towards Pismo Beach. These flows were not modeled, as the emphasis of this test was on the role of Highway 101 in an evacuation and on the efficacy of the design of the mock contraflow plan along the Northern section of Highway 101. The basic statistics associated with all simulations are given in Table 1. Note that the simulation exercise involved 260 census blocks in the San Luis Obispo area.

<table>
<thead>
<tr>
<th>Table 1: Basic statistics associated with the evacuation event</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic Statistics</strong></td>
</tr>
<tr>
<td>18,040 Total Vehicles evacuating</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>260 Total Vehicle Input Locations</td>
</tr>
<tr>
<td>Vehicles are routed based upon dynamic traffic assignment</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>78.6% of San Luis Obispo households evacuate using U.S. Highway Route 101</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

The evacuation event involved a total of 18,040 vehicles (1 per household). This amount can be easily changed as it makes sense in a real circumstance to plan using several scenarios (*e.g.* low estimate of demand, moderate estimate of demand, and a high estimate of demand). The departures of these vehicles were uniformly distributed over the first two hours of the simulation event. This, too, is an important variable. Earlier tests were conducted where all demand departed in the first hour of evacuation. What resulted was a grid-lock situation in which the
software could not reach a set of stable routes or pathways, where many vehicles traveled in circles, as capacity was limited in their movements towards on-ramps. Part of this outcome was the result of erratic routes generated when vehicles had almost no option as to where they could head. When pathways were fixed for each neighborhood in travelling towards their “assigned” highway ramp, this type of problem did not occur, however, significant traffic congestion was experienced throughout the entire area of San Luis Obispo. Examples of this are given in the appendix.

The main results generated for the base case of no contraflow options are given in Table 2. As described above, this simulation involved the use of a calibrated dynamic traffic assignment model. The results represent tabulations made at the 3-hour time mark, after the evacuation event started. At the 3-hour mark, 13,292 vehicles of the 18,040 were still in the process of evacuating.

<table>
<thead>
<tr>
<th>Data type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>measurement</td>
<td>13292</td>
<td>4159</td>
<td>4923</td>
<td>7.2</td>
<td>23865.</td>
<td>903.87</td>
<td>566</td>
</tr>
<tr>
<td>1</td>
<td>Number of vehicles in the network, All Vehicle Types</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Number of vehicles that have left the network, All Vehicle Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Average delay time per vehicle [s], All Vehicle Types</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Average speed [mph], All Vehicle Types</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Total delay time [h], All Vehicle Types</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Latent delay time [h], All Vehicle Types</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Latent demand, All Vehicle Types</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Furthermore, 4,159 vehicles had successfully reached one of the evacuation exits (Atascadero or Pismo Beach). Average vehicle speed during the evacuation was 7.2 miles per hour, and the average delay per vehicle was 4,923 seconds or approximately 45% of the 3 hour period. As vehicle departures were spread out over the first two hours, an average delay of close to an hour and a half suggests that most vehicles spend the majority of their trip in some form of delay, caused by congestion. Note that at the end of the three hour period, 566 vehicles had not yet been able to depart. Overall, the statistics for the base case evacuation indicate a near grid-lock situation with significant delays such that a majority could not reach an exit of the evacuation region within three hours.

Figure 7 depicts the network at the 2 hour time mark. Each arc on the network is coded in a color that represents the average vehicle speed 2 hours after the evacuation event starts. Note many sections of Highway 101 have traffic speeds that range from 6-12 miles per hour, and that the majority of the road network within the City of San Luis Obispo experienced vehicle speeds that averaged less than 6 miles per hour. Given that the majority of the network within the city close to Highway 101 experienced such slow vehicle speeds, one can classify this condition as near grid-lock. When assessing the results of this simulation, one must keep in mind that this is a highly optimistic result for the base case. First, this does not consider any existing traffic on the network when the call for evacuation occurs. Second, this does not account for any trip chaining that may exist in a true evacuation, where a vehicle may leave a home, proceed to another
Figure 7. Map depicting congestion on network at the 2 hour time mark in simulating a non-contraflow scenario. Note those areas colored in pink represent traffic speeds of less than 6 miles per hour.
location to pick someone up, and then proceed to an entrance route on the highway to evacuate. Third, demand for those without cars, people with disabilities, the elderly, and those hospitalized have not been considered. Thus, the results underestimate the demand for those who cannot evacuate without assistance. Finally, the students who are housed on campus at Cal-Poly San Luis Obispo have not been included. Adding these other demands would add significantly to the critical nature of the event and further degrade the traffic flow.

Another way in which we can depict an evacuation is in terms of the number of vehicles that have successfully reached an outlet (or exit) of the evacuation area per given time interval. Figure 8 depicts for the base case the number of vehicles that have left the evacuation area for each half hour time interval (given in seconds). For example, in the first time interval (0-1800 seconds), only a negligible number of vehicles have reached an exit (Atascadero or Pismo Beach).

![Base Case Vehicle Totals](image)

**Figure 8.** The number of vehicles successfully exiting the evacuation area by time intervals in seconds. Note flow totals per interval are quite low. Part of this is associated with very low average speeds on Highway 101 and near grid lock conditions in areas close to Highway 101 in the City of San Luis Obispo.

5. Simulation results for a contraflow based evacuation plan

The mock contraflow plan was based upon reversing traffic flow on South-bound Highway 101 at San Luis Bay Drive to North-bound flow. San Luis Bay Drive is south of the City of San Luis Obispo. Thus, all lanes of Highway 101 through San Luis Obispo are used to handle North-bound traffic. The end of the contraflow section is at Santa Barbara Road at the southern boundary of the City of Atascadero. The plan involves blocking specific on-ramps and off ramps to aid in directing flow for both South-bound and North-bound lanes. Other ramps are reversed
in direction of use so that vehicles can enter and travel northward on what was originally designed for South-bound use. Additionally, traffic crossing most overpasses is to be blocked, forcing traffic that reaches the highway to enter the highway. In preliminary simulations, it was found that because of a mismatch between demand generated to the east of Highway 101 and to the west of Highway 101, traffic circulated in an unusual manner that was not realistic. This situation also made it difficult to calibrate a model using dynamic traffic assignment. Accordingly, this one element was not modeled as a part of the contraflow plan. The Appendix depicts a fixed route plan which is amenable to such route closures within the simulation. The results for the contraflow plan are compared to the non-contraflow plan in Table 3. First, it should be observed that the contraflow plan resulted in average traffic speeds during evacuation of 20.3 miles per hour, whereas in the base case speeds averaged 7.2 miles per hour. From this fact alone, one can assume that evacuation is substantially aided with the use of a contraflow option. Of the 18,040 vehicles departing San Luis Obispo and evacuating using Highway 101, only 4,248 vehicles are still on the network at the end of the three hour time mark. This is substantially lower than the amount of traffic moving on the network at the end of the three hour time period for the base case (that is, 13,292)! This also means that a majority of the demand (12,855) had successfully evacuated and left an exit point at the end of the simulation period, whereas in the base case less than a third of this number had reached an exit in the same amount of time. Overall, one can observe, that in every category, the contraflow plan appears to outperform what would be achieved without contraflow operations. One telling statistic is that the average delay per vehicle for the contraflow plan is 31% of the average delay found for the base case.

<table>
<thead>
<tr>
<th>Data type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non Contraflow</td>
<td>13,292</td>
<td>4,159</td>
<td>4,923</td>
<td>7.2</td>
<td>23,865.</td>
<td>903.87</td>
<td>566</td>
</tr>
<tr>
<td>Contraflow</td>
<td>4,248</td>
<td>12,855</td>
<td>1,528</td>
<td>20.3</td>
<td>7,262</td>
<td>202.71</td>
<td>0</td>
</tr>
</tbody>
</table>

1. Number of vehicles in the network, All Vehicle Types
2. Number of vehicles that have left the network, All Vehicle Type
3. Average delay time per vehicle [s], All Vehicle Types
4. Average speed [mph], All Vehicle Types
5. Total delay time [h], All Vehicle Types
6. Latent delay time [h], All Vehicle Types
7. Latent demand, All Vehicle Types

Figure 9 shows the number of vehicles that have successfully left the area during different time segments of the simulation. For instance, in the time interval of 3600 to 5400 seconds (1hour- 1 ½ hours) approximately 2,900 vehicles were successful in leaving the evacuation area. Note that after the first hour the system reaches a plateau in traffic exiting the system and continues through the third hour. There appears to be a substantial gain in the numbers of vehicles successfully evacuating in each time period for the contraflow case as compared to the base case, except for the first half hour in which few vehicles exited the system in either case. The same caveats hold true for the contraflow case as for the base case, that is, with respect to the issues of
ignoring existing base-flow of traffic on streets and highways, people without cars, people with a disability that prevents them from driving, people hospitalized or in convalescent care facilities, and the student body at Cal-Poly San Luis Obispo.

Figure 9. The number of vehicles successfully exiting the evacuation area by time intervals in seconds for the mock contraflow plan.

Figure 10 displays the network at the 2 hour time mark for the contraflow case. Each arc on the network is coded in a color that represents the average vehicle speed 2 hours after the evacuation event starts. Some of the sections of Highway 101 have traffic speeds that range from 6-12 miles per hour, and there are a number of areas within the City of San Luis Obispo that experience vehicle speeds that average less than 6 miles per hour. If one compares Figure 10 with that of Figure 7, one will see that the contraflow case appears to result in fewer areas of the City and fewer sections of Highway 101 experiencing extremely slow speeds in contrast to the base case.

In a general comparison between the base case and the contraflow case, it is clear that a majority of the residents of San Luis Obispo are able to evacuate within three hours under contraflow, but are not with base case operations. It is important to note that the results for each case might dramatically change given a different departure histogram. For example, spreading demand over a larger time frame may result in better traffic flows in comparison to restricting all departures to be made within the first two hours. Further, if such a model were to be used in fine-tuning an evacuation plan, then a number of different scenarios would need to be run in order to both fine tune a plan as well as identify major bottlenecks that might need traffic control. It is also important to note that there may be specific road issues that are part of a local knowledge base (local transportation engineers and traffic control officers) that need to be included in the traffic simulation. This “local” knowledge cannot be easily recreated and consequently, it is important that local experts be involved in such planning.
Figure 10. Map depicting congestion on network at the 2 hour time mark in simulating a mock contraflow scenario. Note those areas colored in pink represent traffic speeds of less than 6 miles per hour.
6. Discussion of results

Charts and screenshots both indicate significant queues building over time on many sections of the transportation network for the base case. Areas within the City of San Luis Obispo have the longest queues and slowest vehicle speeds which is to be expected given the high population density and corresponding travel demand (traffic inputs). The base case (no contraflow) queuing and congestion may be the primary reason that only 1/3 of the vehicles on the network make it to 'safer' areas away from the Diablo Canyon power plant in the time frame that was modeled. In contrast, the contraflow example yields demonstrably better results, where the majority of vehicles make it to an exit point of the evacuation area and where the average vehicle speed is nearly three times faster. Overall, the “mock” contraflow plan appears to be very promising. Although this is only a “mock” evacuation plan, there are appealing features to this plan in that the capacity to handle traffic heading away from San Luis Obispo has been significantly enhanced. However, there are elements in the mock plan that deserves further scrutiny. They are:

- Alternate routes should be fully utilized for evacuation, most notably State Route 1 (Northwest area of network) and State Route 227 (East area of network). This may mean that more traffic should be diverted from San Luis Obispo and Highway 101, or vice versa. Such an analysis would need to be based upon the DCEP plan and a micro-scale traffic model.

- The mock contraflow plan does not allow vehicles to utilize Highway 101 over- or underpasses, whereas the simulation model results reported here do allow that traffic to occur. This helps to relieve some disparities in travel demand between those neighborhoods on the east of Highway 101 and those on the west of Highway 101. Selected crossing locations can help to balance traffic demand entering Highway 101, fully utilizing the contraflow section and the regular flow section of the highway.

- The simulation model does not consider the possibility of trip chaining, where an individual may start at their place of work, return to their home, pick up someone and proceed to evacuate. This is a more realistic situation in an emergency, and such behavior cannot be captured in this modeling approach.

- The mock evacuation plan is far from complete. One can consider this as an exercise in thinking forward to a possible emergency. Such plans can be complicated and the requirements to fully support such a plan have not been fully analyzed within the context of setting up a contraflow segment. Operating a contraflow plan in Louisiana during hurricane Katrina took a considerable amount of state resources and time to set up. In the case of Katrina, state troopers and parish police had a considerable amount of advanced warning and time to set up the road system for contraflow operations. In a nuclear plant disaster, there may be little warning and the personnel needed to setup a contraflow system may take time to amass.
7. Limitations

The simulation presented here is a best-case type simulation. Traffic is likely to be worse as there are a number of assumptions that have been made. First, the simulation results are based upon 1 vehicle departing per household. This is likely to be a lower bound on the average number of vehicles being used in evacuation. Second, we have assumed that departures times are random with the first two hours of the event. Random uniform departures from traffic input points over the 2 hour window may not reflect trip departure timing during a real evacuation. This assumption does not necessarily match what might be expected in actual behavior, as little data has been collected for such events and a complete understanding has yet to be developed. Although, demands for major evacuation events like hurricanes are better understood, these often happen over larger time frames, and such events do not necessarily represent the urgency that might be present for a wildfire, tsunami, or nuclear disaster. Third, special demands like hospitals, nursing homes, the homeless, those who don’t own cars, and those living at Cal-Poly San Luis Obispo have not be included. The bottom line is that a contraflow plan for this area appears to be beneficial, aiding in substantial increases in average travel speeds and in larger numbers of vehicles leaving considerably earlier than what happens in the base case (do nothing).

8. Suggested Future work

The objective of this project was to capture the essence of a mock contraflow plan involving an emergency at the Diablo Canyon Power Plant. Although many of the main problem elements were captured to the point that a simulation model could be applied, there are a number of remaining issues that should be considered in any future improvements to the VISSIM model addressing. They include:

1) Current traffic inputs should be overlaid on aerial imagery and the placement be assessed. It may be possible to move these inputs to correspond better with the actual locations of housing within each census block.

2) Highway 101 entrance ramp daily traffic counts supplied in the appendix of the Caltrans plan could be used to calibrate traffic flow. These counts could essentially serve as a scaling factor to help determine how heavily each entrance ramp will be used.

3) Network geometry should be corrected using aerial imagery. Only selected intersections at Highway 101 were corrected. This may not materially change the results of the model as the attributes of the links dictate use in a simulation but improve its use in visualization.

4) Traffic signal timing should be implemented, and reduced speed areas and conflict zones defined for the entire network. Also, fine tuning of merging behavior is necessary. Both tasks can be very time consuming. Collecting signal settings for the city and integrating them would help to close many of the remaining gaps in the model developed here.
5) Plume spread model(s) could be integrated with the traffic simulation model to assess radioactive material exposure risk during the evacuation.

Beyond the work involved with the simulation effort using VISSIM, there are several problems that should receive attention. The first of these is the development of a model that helps estimate the time it will take to amass resources and set up a contraflow plan in an emergency. In fact, Caltrans should develop supply models which estimate how much time it would take to reach any part of their system with a prescribed set of equipment and trained personnel. A second problem of major importance is the development of models which can estimate the demand for evacuation on the part of those not using personal vehicles and those requiring assistance (e.g. those who need public transit). Further work should also involve modeling when evacuation demand is exerted during an emergency. Finally, more accurate methods should be developed for determining the location of individuals by time of day. The simulation here is based upon the assumption that everyone starts at their home and evacuates. This is clearly a poor assumption during daytime hours, when many people are at school or work. Models like SimAgent may be employed for this purpose.
Appendix: Simulation for a contraflow evacuation plan using fixed routes

Evacuation modeling can be accomplished using linear flow models. This type of modeling technique has been used in building egress models as well as wide area evacuation, including emergency evacuation planning zones around nuclear power plants. Perhaps one of the most widely accepted approaches is one based upon paths. As an example, one form of that has been used to generate an estimate of evacuation effectiveness is the following:

1) Generate for each leaving vehicle a departure time.
2) For the vehicle that has not yet left and has the earliest departure time, identify the shortest path to leave based upon an estimate of congestion generated by those who have already left and chosen a route. Assign this vehicle to that path which is the shortest according to current trip assignments.
3) Have all vehicles left? If yes, stop and tally the times vehicles reached an exit to the evacuation region. If not, then return to step 2.

This approach can be used to give a rough approximate of the effectiveness of an evacuation plan. An alternate form of this is to define fixed routes for sets of individuals in leaving an area. For example, in the San Luis Obispo area there were 260 different individual neighborhoods that are used for sources of vehicles leaving the area. For each of these 260 neighborhoods (or census blocks) we can define a route that those vehicles will take to leave the area. We assume here that people will not make dynamic route changing decisions, but use what looks to be logically the route of first choice. This type of option is supported in the PTV VISSIM software as well. In order to perform a simulation using this option, it was necessary to code a fixed route for each of the neighborhoods. The simulation is then used to model congestion associated with the fixed route plan. This approach is just as efficacious as the path based model described above. In fact, in many ways it can be considered to be better than that approach as it more accurately depicts individual route congestion. In this appendix, we present the results of a simulation based upon fixed routing for each census block.

The assumptions used in the example presented here are the same as those presented in Table 1, with the exception that each of the 260 neighborhoods have a defined route for exiting the area and that all demand is set up to leave in the first hour of the simulation. Whereas, the dynamic traffic assignment results presented in the main section of this report are specified for evacuation demand spread out over two hours, we assumed for the fixed route analysis a more intense, shorter duration of evacuation demand.

At the end of the first hour of simulation, 2,005 vehicles (11.2%) have passed Cuesta Grade. This represents flow that has passed safely over the grade heading to Atascadero. At this same time 6,226 vehicles (34.9%) have passed the last entrance ramps on Monterey Street in San Luis Obispo. This means that in the first hour, approximately a third of the traffic demand has reached a point where they have merged onto Highway 101 and are traveling north from San Luis Obispo.

The evacuation event can be analyzed from the perspective of each onramp and sections of Highway 101. Rather than show details of each highway element, data in this appendix is
summarized for all ramps, those on the freeway north of Cuesta Grade and those on the highway north of the Monterey Street onramps. Figure 11 presents a chart which gives the distribution of vehicles reaching the northern most collector point over the time of the simulation. This depicts the number of vehicles having reached north of Cuesta Grade per minute. Note that the time lag in traffic reaching this collector point is approximately 22 minutes. After 22 minutes the traffic reaching this point begins to increase until it averages a flow of approximately 60 vehicles a minute. To serve approximately all 18,000 vehicles would take up to 4 hours. Figure 12 gives this same distribution for those cars passing just north of the Monterey Street exit at the northern boundary of the City of San Luis Obispo. This figure shows that the number of vehicles having merged onto Highway 101 and begin their trip to Atascadero starts with almost no lag in time from the beginning of the evacuation event. The traffic volume per minute quickly ramps up to an average that is between 100 and 110 vehicles per minute. Much of this volume is predicated on the number and capacity of entrance ramps as well as the time in which it takes to merge into the traffic lanes on Highway 101.

![Figure 11: Total vehicles per minute passing data collector on Route 101 at end of contraflow section](image)

Figure 13 depicts the number of vehicles merging onto Highway 101 per minute over all entrance ramps. This shows that the number of vehicles entering the system quickly ramps up to 180 vehicles per minute, but as congestion starts on Highway 101, the entrance flow begins to decline. After the first fifteen minutes the traffic entering onto Highway 101 declines to an equilibrium rate of approximately 110-115 vehicles per minute.

As the traffic begins to increase, average vehicle speeds on Highway 101 begin to decrease. This phenomena can be understood by calculating the maximum delay that is experienced by any one
vehicle entering the system. Figure 14 depicts the maximum queue delay faced by those vehicles reaching the end of the contraflow section. Note here that queue delays for cars reaching this point reach 1500 seconds at the end of the hour. This means that of the cars reaching this point, the maximum queue delay experienced was approximately 25 minutes.

Figure 12: Total Vehicles per minute passing data collector on Route 101 after the last entrance ramp at San Luis Obispo heading north.

Figure 15 depicts a similar trend for the maximum queue delay faced by vehicles having passed the Monterey Street onramp, except that the maximum delays begin to ramp up from zero almost immediately after the start of the evacuation event. Here the maximum delay experienced by any one vehicle reaching this location at the end of the first hour is 50 minutes. That is, almost all of the travel experienced by that vehicle in that hour was queue delay! This means that there is considerable delay experienced by drivers in reaching Highway 101.

To understand where congestion occurs during the evacuation event and the fixed route scenario, maps were produced for three times: 20 minutes, 40 minutes, and 60 minutes. The images produced by VISSIM show the average speed [mph] of each vehicle on the network after 20 minutes, 40 minutes, and 60 minutes of simulation time. Highest speeds are indicated by green colors and lowest speeds by purple, with yellow at the midpoint. Figure 13 depicts the status of the system after 20 minutes. Note that the average speeds on Highway 101 are principally colored yellow, indicating that the speeds averaged 21-30 miles per hour. There are some locations on Highway 101 which experienced larger delays and are colored brown to red. In the City of San Luis Obispo, delays on a number of arterials are colored magenta or red. This means
that speeds on these streets ranged from 0 to 6 mph (magenta) and 6-12 mph (red). Thus, the traffic in the city is congested even after the first 20 minutes over many of the major streets.

**Figure 13:** Total Vehicles per minute passing data collectors on all Highway 101 entrance ramps.
Figure 14: Maximum queue delay time on Route 101 at the end of the contraflow section

Figure 15: Maximum queue delay time on Highway 101 after last entrance ramps
Figure 16: Maximum queue delay time on all Highway 101 entrance ramps
Figure 17: Vehicle speeds 20 minutes after evacuation begins
Figure 18: Vehicle speeds 40 minutes after evacuation begins
Figure 19: Vehicle Speeds 60 minutes after evacuation begins.
Figure 18 gives the view of traffic congestion at the 40 minute time period. Here it can be seen that the traffic speeds on Highway 101 have not materially changed, but congestion in the City has increased, where many street segments that were coded as red at the 20 minute mark are now colored in magenta at the 40 minute mark, indicating that traffic has been further slowed down. Note that some street segments colored in yellow at the 20 minute mark are now colored in magenta at the 40 minute mark. Also note that congestion has spread to outlying streets in the city. This pattern of congestion extends even further when moving from the 40 minute mark to the hour mark (Figure 19). It should not be a surprise that the constraints on fast evacuation are associated with the capacity of the highways to carry that traffic as well as the ramp capacities in accommodating inflow traffic. One must note that such patterns of congestion would have advanced faster with higher levels of congestion within the city without a contraflow setup.

It is important to note that this appendix presents results for a fixed route plan for all residents. This mimics the type of modeling that has been done in the past with fixed routes (without dynamic traffic assignment). The results here differ from the contraflow plan generated for dynamic travel assignment in one principal way: travel demand is spread out over one hour and not two hours. In either case (dynamic or fixed), a complete evacuation can be accomplished in approximately four hours. This estimate, of course, ignores possible delay effects of trip chaining, ignores populations needing assistance, does not include the impact of Cal-Poly San Luis Obispo, and ignores current traffic levels on streets and highways. What is important is that there appears to be a very real benefit to designing a contraflow plan, assuming local resources are ready and available to support such a plan.