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BREAKDOWN PROBABILITY MODEL AT FREEWAY-RAMP MERGES
BASED ON DRIVER BEHAVIOR

By

ALEXANDRA KONDYLI

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2009

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To my parents

ACKNOWLEDGMENTS

I would like to thank my graduate advisor, Dr. Lily Elefteriadou of the University of Florida for her insights and guidance throughout this dissertation and her valuable support throughout all my years of study. I would also like to thank the remaining members of the committee, Dr. Scott Washburn, Dr. Yafeng Yin, Dr. Siva Srinivasan, and Dr. Orit Shechtman, for their assistance and their advices.

I would like to thank my friends and fellow students of the University of Florida Transportation Research Center for their assistance during the data collection effort. Without them, it would be impossible to complete this effort. Special thanks are addressed to Aaron Elias, George Chrysikopoulos, Dimitra Michalaka, Seokjoo Lee, Grady Carrick, Kevin Heaslip, Irene Soria, Daniel Sun, and Cuie Lu. I am also grateful to the staff at the Jacksonville Traffic Management Center for their assistance and accommodations during the data collection effort. Above all, I am grateful to my parents, Apostolos and Maria for their love and support.

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Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

**BREAKDOWN PROBABILITY MODEL AT FREEWAY-RAMP MERGES
BASED ON DRIVER BEHAVIOR**

By

Alexandra Kondyli

August 2009

Chair: Ageliki Elefteriadou
Major: Civil Engineering

A freeway-ramp merging model that considers vehicle interactions and their contribution to the beginning of congestion was presented. Focus group discussions were conducted to attain knowledge about drivers' thinking process when merging. Three types of merging maneuvers were considered (free, cooperative, and forced), based on the degree of interaction between the freeway and the ramp merging vehicle. Field data collection was undertaken to quantify the effect of individual driver characteristics on their merging decisions and associate those with the breakdown occurrences at the freeway-ramp junctions. The data collection entails observations of participants driving an instrumented vehicle and simultaneous video observations of the freeway during these experiments. Behavioral characteristics of the participants were also evaluated.

The collected data were used for calibrating driver behavior models that pertain to ramp vehicles' gap acceptance decisions and freeway vehicles' decisions to decelerate, change lanes or not interact subject to the ramp merging traffic, considering their behavioral attributes. A merging turbulence model was developed that captures the triggers for vehicle decelerations at the merging areas. The merging turbulence model due to vehicle interactions was evaluated

through macroscopic observations at near-congested conditions. It was shown that the merging turbulence can be used as an indicator of the breakdown events.

CHAPTER 1 INTRODUCTION

Traffic Operations at Freeway-Ramp Merging Segments

Freeway-ramp merging segments are important components of the freeway facilities since they connect the freeway system and the adjacent arterial network, and also they feed traffic into the freeway. These segments are also the source of dynamic interactions, as they involve the merging of two traffic streams. Conflicts occur because these segments usually serve as physical bottlenecks (acceleration lane is dropped after some length), and the two traffic streams are competing for the same space. The literature has described the dynamic interactions between the two traffic streams as either cooperative (through vehicles move to the inner lanes, or yield to create gaps for the merging vehicles) or competitive (merging traffic forcing its way into the freeway, causing the through vehicles to decelerate). It has also been observed that the composite behavior of acceleration and gap acceptance of the merging traffic and the cooperative behavior of the freeway traffic can result in conflicts and even congestion.

In the current version of the Highway Capacity Manual (HCM 2000), the analysis of a freeway facility is based on segmenting the facility to basic freeway segments, ramps and ramp-junctions and weaving segments, neglecting possible interdependencies between the different freeway segments, and the impact of these on capacity (TRB, 2000). The Ramps and Ramp Junctions methodology (Chapter 25, HCM 2000), defines the ramp influence area to be a 1,500 ft long segment downstream of the gore (which includes the acceleration lane and the two outmost lanes of the freeway) and the operations of vehicles within that segment is the focus of the analysis. An illustration of the ramp influence area as well as other important variables used in the HCM methodology is provided in Figure 1-1.

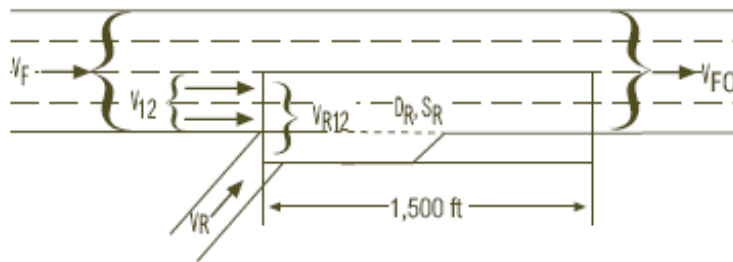


Figure 1-1. Critical ramp junction variables (Source: HCM 2000–Chapter 25).

In addition, the HCM 2000 provides a clear connection between the definition of capacity and the breakdown occurrence. According to the manual, capacity is defined as “...the maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period, under prevailing roadway, traffic and control conditions” (HCM 2000, p. 2-2). Inherent to this definition is the notion that once capacity is achieved, the freeway facility will break down (transition from free-flowing conditions to congestion, i.e., level of service F); otherwise there is still the potential of observing higher maximum flows. This is also associated with the development of queues upstream of the bottleneck, indicating excess of demand.

In the field, capacity at ramp junctions is typically measured at the bottleneck (as shown in Figure 1-2), where vehicles are in discharge state. Capacity cannot be measured inside the queue because the flow there is restricted by the downstream capacity (beyond the front of the queue) (Elefteriadou et al., 2006). On the other hand, capacity at basic freeway segments cannot be measured in the field, as the literature has not shown any evidence that these segments can break down without the presence of a bottleneck or other sources of demand restriction.

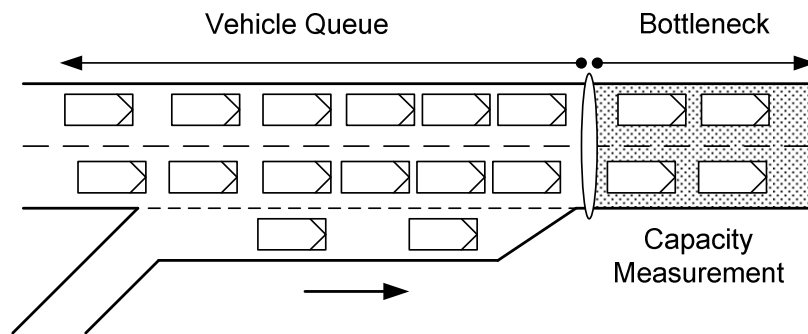


Figure 1-2. Bottleneck location at freeway-ramp merging segments.

In addition to the measurement issues of capacity, the literature has examined various definitions of capacity. Suggested flow rates from the literature that define capacity are: (1) the maximum pre-breakdown flow; (2) the average pre-breakdown flow; and (3) the flow rate after the upstream queue has formed (Elefteriadou et al., 2006). Irrespective of whether capacity is defined as the maximum or the average pre-breakdown flow or queue discharge flow, the literature has shown that this is not a fixed number, but rather a random variable (Persaud and Hurdle, 1988, 1991; Agyemang-Duah and Hall, 1991; Minderhoud et al., 1997; Lorenz and Elefteriadou, 2001; Brilon, 2005).

Regarding the breakdown events and the beginning of congestion at freeways, research has shown that breakdown does not always occur at the same demand levels (Elefteriadou et al., 1995; Okamura et al., 2000). Moreover, the HCM 2000 states that (pp. 25-3) "... the turbulence due to merging and diverging maneuvers does not affect the capacity of the roadways involved, although there may be local changes in lane distribution and use", but field observations show the opposite. The data show that at merging segments, the presence of platoons of ramp vehicles that want to merge and "squeeze" on the freeway (Elefteriadou et al., 1995; Kerner and Rehborn, 1996, 1997; Yi and Mulinazzi, 2007) may have "invasive influences" on the freeway vehicles, such as decelerations and lane changes. These observations lead to the conclusion that

breakdown events at freeway merging segments are associated with the interactions between the two competing traffic demands, and this might explain the observed variability in capacity.

Driver Behavior at Freeway-Ramp Merging Segments

In the previous section it was shown that driver behavior affects capacity and traffic operations at freeway-ramp merging segments. Based on Rasmussen's model (1986) driver behavior can be divided into a hierarchical structure with three levels:

- Strategic level: At this level the driver determines its goals and plans its route. The decisions made at this level, are affected by driver's familiarity with the transportation network and by any available real-time information.
- Tactical level: At this level the driver selects certain maneuvers to achieve short-term objectives (e.g. interactions with other drivers). Here, driver behavior is influenced by both the most recent action, and the driver's goals at the highest level.
- Operational level: At this level, the driver performs real actions such as steering, accelerating, and gearing. These actions are skill-based and mostly done automatically, with little conscious effort.

Several interactions can be observed between the different driving tasks: At the strategic level, the driver makes decisions related to the path choice and to determine a schedule for the trip (e.g. in terms of desired arrival time). Tactical decisions are affected by the vehicle's driving neighborhood and by the strategic concerns. For example, the driver has to be in the correct lanes in order to follow the path plan. If the trip schedule is not kept or in the presence of traffic information the driver may decide to reevaluate the path plan and switch paths. The choices of speed and lane are translated to mechanical actions to control the vehicle. In turn, the outcome of these actions affects the positioning of the vehicle within its neighborhood.

Travel behavior researchers study drivers' strategic choices (level 1) while the operational behavior (level 3) is studied in human factors research. Driving behavior models capture tactical decisions at level 2. The most notable driving behavior models are acceleration and lane changing models. Other important driving behaviors include negotiation of intersections and

merging areas and response to signals and signs. Two of the most important microscopic models in traffic engineering, car-following and lane changing, are tactical-level models.

Car-following models describe the vehicle's behavior while following the leading vehicle. Car-following models assume that the subject vehicle reacts to the leader's actions. Recent research developed general acceleration models that also capture the behavior of drivers in other situations; such as in car following and free-flow conditions. Based on these models, drivers that are not close to their leaders may apply free-flow acceleration to reach their desired speed. Lane changing models have mostly been developed for micro-simulators. The lane changing process is normally modeled in two steps: (i) the decision to consider a lane change and (ii) the execution of the lane change. Lane changes are further classified as either mandatory (MLC) or discretionary (DLC). MLC are performed when the driver must leave the current lane, such as in freeway-ramp merging segments. DLC are performed to improve vehicles' driving conditions. In the vicinity of freeway-ramp junctions, mandatory, but also discretionary lane changes take place (DLC are performed upstream to avoid conflicts with the ramp merging vehicles). Recent research categorizes lane changes depending on the degree of interference with the adjacent vehicles, to free, cooperative and forced lane changes. Lane changes are usually modeled using gap acceptance models.

Existing driving behavior models have several limitations. An important limitation is that inter-dependencies between vehicles' behaviors are not addressed, as different behaviors are modeled separately. Most significantly, the combination of merging and lane changing behavior on the traffic operations of the freeway is ignored. Similarly, factors that influence drivers' decisions while performing (or being affected by) merging maneuvers have not been studied from the drivers' perspective. Lastly, although driver behavior parameters are crucial for the

investigation of breakdown occurrences at freeway-ramp merges and gap acceptance decisions, these are not explicitly incorporated in current models. The unavailability of driver-related data may lead to inaccurate models since decisions at the tactical level are very much dependent on the interactions between individuals.

Objectives of the Dissertation

The objectives of this research can be summarized as follows:

1. To develop a ramp merging model that considers the merging process near congested conditions, as it is perceived by individual drivers. The scope of this objective includes the following elements:
 - The ramp merging model should address all different types of merging maneuvers, such as free, cooperative and forced merging.
 - The model should capture the vehicle interactions that occur during the merging process. It should also account for stochasticity of driver behavior in accepting gaps and in making decisions, for the same driver and across all drivers. An in-depth analysis of the drivers' perspective is required to collect information about factors that affect their decision process and their behavioral differences. The model should also consider the geometry of the merging area as a factor.
 - The behavior of the freeway vehicles upstream of the merge point (lane changing activity) should be addressed in all relevant components of the merging model. Evaluation of the effect of the lane changing behavior on the distribution of gaps, and therefore the merging process, will be performed.
 - The effect of cooperative and forced merging on the traffic conditions should also be addressed. The research will quantify the impact of these maneuvers on the probability of breakdown.
2. To develop an analytical model that can determine the probability of breakdown on the freeway given the behavior of both mainline and ramp merging vehicles.

CHAPTER 2 LITERATURE REVIEW

The chapter summarizes past research related to the estimation of capacity at freeway ramp merging segments and the description of the breakdown phenomenon at these locations, either through observational studies or through modeling of the driver behavior. The first section describes previous research efforts to model the behavior of the merging vehicle (acceleration, lane changing, and gap acceptance) and discussion on specific models that have been used in microsimulation programs follows. The next section presents findings regarding the merging process under complete congested conditions. Following that, a summary of literature review on driver behavior-related studies is presented. This chapter concludes with a summary of the literature findings and their limitations.

Capacity and the Breakdown Process at Freeway Ramp Merging Segments

According to the current version of the Highway Capacity Manual (HCM 2000) the capacity of a facility is defined as “...the maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period, under prevailing roadway, traffic and control conditions (HCM 2000, p. 2-2).” This definition implies that once capacity is achieved, the facility will break down; otherwise capacity has not been attained (HCM 2000 also notes that capacity is the upper boundary of LOS E). Thus, the observation of breakdown is closely related to the capacity of a facility.

Several studies that focused on the capacity of freeway segments and the investigation of the speed/flow/density relationships have observed traffic flow and the breakdown process in the vicinity of ramp merges that usually serve as freeway bottlenecks. The findings of these studies vary significantly, and this indicates that (i) capacity is stochastic in nature, (ii) individual drivers' behavior may trigger the breakdown phenomenon, (iii) vehicles merging onto the

freeway from an on-ramp may create traffic turbulence, which can result in freeway flow breakdown.

The Nature of Capacity

According to the definition of capacity used by the HCM 2000, each facility type has different capacity values; however these remain invariable for facilities with similar geometric and traffic conditions. For example, capacity values are given as 2,250 passenger cars per hour per lane (pcphpl) for freeways facilities with free-flow speeds of 55 miles per hour (mph), and 2,400 pcphpl when the free-flow speed is 75 mph (under ideal geometric and traffic conditions).

While the current version of the HCM treats capacity as a deterministic value that depends on the geometric conditions of the facility, there is a significant amount of recent literature based on field data observations, which contradicts this argument, and proposes that capacity is stochastic in nature. Researchers have come to acknowledge the stochasticity of capacity, however this has raised several other questions related to which value of flow rate should be measured (maximum pre-breakdown flow rate, pre-breakdown flow rate, discharge flow rate), where and when it should be measured, what time interval should be used, and if it is a random variable what percentile of the distribution should be used as the descriptive statistic. The remaining of this section presents proof from the literature that capacity rather stochastic than deterministic in nature.

Persaud and Hurdle (1991) examined various definitions and measurement issues for capacity; such as maximum flow, mean flow, and expected maximum flow definitions. Based on observations of field data at a three-lane freeway site, over three days, they recommended that the mean queue discharge flow is the most appropriate, partly due to the consistency they observed in its measurement.

Agyemang-Duah and Hall (1991) collected data over 52 days on peak periods to investigate the capacity drop issue when a queue forms, and to recommend a numerical value for capacity. They showed that the distribution of pre-queue flows and queue discharge flows in 15-minute intervals, with the first one slightly more skewed toward higher flows. They recommended two capacity values: one for pre-breakdown conditions at 2,300 pcphpl, and one for post-breakdown conditions at 2,200 pcphpl. They recognized the difficulty in defining and measuring capacity, given the variability observed.

Wemple et al. (1991) also collected near-capacity data at a freeway site and discussed various aspects of traffic flow characteristics. High flows (above 2,000 vphpl) based on fifty 15-min time periods were identified, plotted, and fitted to a normal distribution, with a mean of 2,315 vehicles per hour (vph), and a standard deviation of 66 vph.

Elefteriadou et al. (1995) developed a model for describing the process of breakdown at ramp merge junctions. Observation of field data showed that, breakdown may occur at flows lower than the maximum observed, or capacity flows. In addition, it was observed that, at the same site and for the same combination of ramp and freeway flows, breakdown may or may not occur. Elefteriadou et al. developed a probabilistic model for describing the process of breakdown at ramp merges, which gives the probability that breakdown will occur at given ramp and freeway flows, and it is based on the occurrence of ramp-vehicle clusters.

Minderhoud et al. (1997) also studied the random nature of capacity by considering stochastic theories for estimating capacity. Similar to Wemple et al. they proposed a normal distribution to describe the statistical properties of capacity. They were also the first who proposed to estimate the distribution of capacity using the Product Limit Method based on field observations. They borrowed the theory from lifetime statistics analysis, assuming that a system

failure (traffic breakdown) occurs when there is traffic spillback from the bottleneck; however, they used flow observations taken from the upstream location. Thus, in this way they included congested data points in the analysis, that are inside the queue, and volumes at that location may be lower than the maximum possible. Brilon and Zurlinden (2003) and Brilon (2005) built upon this method, although they assumed as events of failure cases of distinct breakdown observed at the bottleneck and not upstream (also assuming that congestion does not propagate from downstream). Brilon and Zurlinden (2003) evaluated various mathematical functions and they concluded that the Weibull distribution provides the best fit to the empirical data.

Sarvi and Kuwahara (1999) performed an evaluation study of the merging capacity in Tokyo Metropolitan Expressway to determine the impact of geometric design and traffic characteristics on the capacity of seven merging sections. Based on their research, capacity is positively related to the taper length, but no correlation with the length of the acceleration lane was found. This may occur because under congested conditions the drivers try to merge soon after entering the acceleration lane. Sarvi and Kuwahara also found that the merging capacity increases slightly with increasing relative grade (ramp grade minus the freeway grade). With respect to the merging ratio (percentage of merging flow), the evaluation concluded that capacity increases when the merging ratio increases up to 0.32 and then decreases. Therefore, the maximum capacity was observed for a 0.33 merging ratio, but it is noted that additional data are required to identify the maximum capacity.

Okamura et al. (2000) collected data on several freeway sections in Japan over a whole year where they observed several breakdown events. They considered that freeway capacity is the average of the breakdown volumes (i.e., traffic volume immediately before the breakdown event), which varied over a wide range.

Lorenz and Elefteriadou (2001) conducted an analysis of speed and flow data for two freeway bottlenecks in Toronto, Canada. They suggested incorporating a probability of breakdown in the definition of freeway capacity, such as: "...the rate of flow (in pcphpl and for a particular time interval) along a uniform freeway segment corresponding to the expected probability of breakdown deemed acceptable under prevailing traffic and roadway conditions in a specified direction." The value of the probability component should correspond to the maximum breakdown risk deemed acceptable for a particular time period. According to this definition, on the average, highest flows occur before the breakdown.

Sarvi et al. (2007) performed an analysis of the macroscopic observations on driver behavior, and showed that capacity (measured after the onset of congestion: i.e., discharge rate) varies from one bottleneck location to another, and its range is between 1,679 and 2,068 vphpl. An important finding of this research is that capacity at merge junctions were generally lower than capacity at other freeway segments.

Breakdown at Freeway Ramp Merging Segments and Its Causes

Buckley and Yagar (1974) observed the breakdown phenomenon at an entrance ramp or lane drop. According to their observations, at the entrance ramp drivers merge into minimal gaps in the adjacent lane, and as they move downstream, they tend to increase their spacing to a more acceptable distance. This occurs when initially drivers decelerate in a car-following mode, and consequently, if one driver slows down then those upstream will need to decelerate more rapidly. They suggested that this shock wave moving upstream is seen as the flow breakdown, which becomes the long-term slow-and-go traffic condition observed upstream of the lane drop.

Elefteriadou et al. (1995) collected data using four video cameras along the ramp merge area at two bottleneck locations, and they concluded that the breakdown was associated with the presence of vehicle clusters coming from the on-ramp. Based on their observations, the ramp

vehicle clusters would “force” their way into the freeway and this would result in vehicles slowing down and eventually the following vehicles would reduce their speed, creating an overall sudden speed drop.

Similar to Elefteriadou et al. (1995), Yi and Mulinazzi (2007) found that the influences of ramp vehicles on freeway vehicles (also defined as “invasive-influences”) are related to the presence of persistent platoons on the ramps. More specifically, they found that the number of evasive events (slow down or change lanes) increases and the standard deviation decreases with the merging platoon size. They note that these invasive-influences of the ramp vehicles may cause the freeway vehicles to slow down and even change lanes. For the model development, they observed the brake-light indications and lane change maneuvers to account for the evasive behavior of the freeway vehicles that travel on the shoulder lane. They also defined the following three merge situations depending on the arrival patterns:

- Free Merge (FM): random arrival of ramp vehicle that does not interact with the freeway vehicle,
- Challenged Merge (CM): ramp vehicles conflict with freeway vehicles on the shoulder lane before merging, and
- Platoon Merge (PM): clusters of ramp vehicles force their way ignoring the priority order, and trigger invasive-influences to the freeway vehicles.

The significance of the invasive-influence on the shoulder lane traffic was estimated by considering: (i) the distribution of traffic on that lane; i.e., less traffic on the shoulder lane means higher invasive-influence, and (ii) the speed decrease of the shoulder lane caused by the persistent platoons. Lastly, the authors proposed alternative LOS indicators that correspond to these relationships between the invasive-influence with volume shift and the speed reduction.

Kerner and Rehborn (1996, 1997) defined the breakdown phenomenon as the transition from free-flow to synchronized flow (average speeds are almost synchronized in different lanes).

Based on data from German highways, the free-flow to synchronized flow transition was detected from the abrupt changes in the average speed. They stated that in bottlenecks, breakdown occurs due to local speed decrease and density increase that is observed when on-ramp vehicles “squeeze” on the highway or due to unexpected speed decrease and lane changing activity.

Daganzo et al. (1999) presented a model describing traffic behavior, which assumes that vehicles respond to changes in the speed of the lead vehicle in the same fashion, irrespective of the past history. They defined the “deceleration disturbance” as occurring when one of the vehicles in the platoon decelerates and allows a gap to grow in front of it to allow another vehicle to merge in. This causes the following vehicles in the platoon to decelerate as well. Eventually, the entire platoon returns back to the original speed, causing a wave to travel within the platoon and propagate upstream. This results in further instabilities and perturbations, which lead to higher densities and the development of “jam” states. They also defined “acceleration disturbance” to occur when a vehicle accelerates and closes the gap in front of it. They concluded that if the acceleration disturbances are persistent, then the queue disturbances could propagate forward and reduce the flow through the bottleneck.

Daganzo (2002), assuming two types of drivers (fast-moving and slow-moving), modeled the freeway breakdown event at a freeway ramp merging segment, as follows: Fast moving vehicles stay in the passing (left) lane, willing to accept shorter headways, while on-ramp vehicles enter and stay in the shoulder lane. Further downstream of the merge, fast-moving vehicles that had entered from the on-ramp leave the shoulder lane and merge into the passing lane; thus they increase the passing-lane flow (this is defined as the “pumping mechanism” as the drivers are willing to accept reduced headways and let the on-ramp vehicles merge). In high and uncongested flow, fast-moving

vehicles follow each other in small headways, suggesting that they are “motivated” by their desire to pass. When the through and/or the merging flow is high, the passing lane becomes saturated downstream of the merge (because of the merging fast-moving vehicles), and a shockwave will move further upstream. This also means that the passing-lane speed will decrease near the merge, causing the fast-moving vehicles to lose their “motivation” to follow closely and change lanes to equalize speeds; thus the queue on the passing lane eventually spills over to the shoulder lane. An evaluation study of Daganzo’s theoretical model was performed by Banks et al. (2003), where it was concluded that some of the phenomena described in Daganzo’s theory do occur, but not at all locations, and that the underlying assumptions were oversimplified. More specifically, Banks et al. verified the increase in time gaps (loss of motivation) but only at one site, but contrary to Daganzo’s model (and other literature), the speed equalization does not take place at all locations. In addition, they did observe redistribution of flow among lanes, even though the speeds were not equalized, and distinction between capacity and discharge flow were not observed downstream from queues (as predicted by Daganzo).

Driver Behavior Models for Merging Maneuvers

Several studies have investigated the maneuvering decisions in order to model driver behavior. These models are mostly valuable to microscopic simulators but also to safety and capacity analysis where aggregate traffic flow characteristics can be obtained from modeling individual drivers’ behavior.

Generally, the literature on driver behavior models has studied mainly three significant topics: acceleration, lane changing and gap acceptance. The acceleration models try to capture the parameters that affect drivers’ acceleration decisions and process, while the drivers are either in a car-following situation or not. Therefore, these models can be grouped (Toledo, 2003) into (1) car-following acceleration models (drivers reacting to the behavior of their leaders), and (2)

general acceleration models. This chapter provides an overview of the acceleration models that were specifically developed to describe the acceleration of vehicles involved in merging situations (usually, these models are focused on the ramp vehicles and the lag vehicles that approach the merge area).

Typically, the lane changing models found in the literature contain two steps: the lane selection process and the lane changing execution process, where gap acceptance formulations are used for the model development. In addition to that, these models distinguish lane changes into two categories: (1) discretionary lane changes (DLC) and (2) mandatory lane changes (MLC). Discretionary lane changes are performed in order for drivers to improve their position in the traffic stream. Mandatory lane changes are performed when drivers must leave the current lane, in order to follow a specific route, such as in merging from the acceleration lane on the freeway, or because of a lane drop or lane closure due to work zone activity.

The literature review included in this section, provides a discussion on all models related to MLC, since this type of lane changes describes the ramp merging behavior. A description of specific DLC models that were developed in conjunction with components for MLC is also available, because this type of lane changes can be observed at the vicinity of ramp junctions, as the mainline vehicles may choose to avoid any disruption from the merging vehicles. Past research focused on the development of merging models integrating both gap acceptance and acceleration decisions is also provided in this section.

Modeling Acceleration Behavior for MLC

Significant amount of research has focused on modeling the acceleration of either the ramp or the freeway vehicles near the merge area. Kou and Machemehl (1997) presented a methodology for modeling the acceleration-deceleration behavior of ramp vehicles. Merging vehicle position data and freeway and ramp volume data from both parallel and taper ramps were

obtained and analyzed (both long and short segments). The volume data cover off-peak and peak periods; however fully congested conditions were not included.

In short acceleration lanes, most of the traffic (approximately 70 percent) merges at the section where the acceleration lane width decreases from 12 ft to zero (parallel-type) or at the section immediately after the gore, where the acceleration lane width drops from 12 ft to 9.5 ft (taper). At long acceleration lanes it was found that the merging position is not affected by the flow levels, which does in fact contradict the initial hypothesis that the larger the freeway and ramp flow rates the longer the distance ramp vehicles travel in the acceleration lane.

No significant relationship was found between ramp vehicles' speed and distance to complete the maneuver, or between time to complete the maneuver and time lags with the freeway lead/lag vehicles; however, this may be the result of limited data availability. Finally, they did conclude that as the speed differential between the ramp vehicle and the freeway lag vehicle increases, the merging percentage decreases.

The ramp vehicle acceleration-deceleration model was based on the stimulus-response concept implemented in the car-following models, with respect to the distance lag, D . The methodology was expanded linearly to incorporate the influence of the freeway vehicles and the ramp geometric constraints. Solving for the non-linear regression for $D = 0, 18.29, \text{ and } 36.58 \text{ m}$ (0, 60, and 120 ft) yielded that the best calibrated acceleration-deceleration model was for $D = 18.29 \text{ m}$ (60 ft):

$$\begin{aligned} \ddot{X}_r(d + 18.29) = & -2.145 + 0.002 \frac{\dot{X}_r^{1.092}(d + 18.29)}{[X_r(d) - X_{lag}(d)]^{0.135}} [\dot{X}_{lag}(d) - \dot{X}_r(d)] \\ & - 0.020 \frac{\dot{X}_r^{1.092}(d + 18.29)}{[X_{lead}(d) - X_r(d)]^{0.699}} [\dot{X}_r(d) - \dot{X}_{lead}(d)] \\ & + 3.484 \frac{\dot{X}_r^{1.092}(d + 18.29)}{[L - X_r(d)]^{1.726}} [\dot{X}_r(d)] \end{aligned} \quad (2.1)$$

Where:

- $X_{ri}(d_j)$: Location of ramp vehicle i when it passes the fiducial mark j ,
 $X_{flagi}(d_j)$: Location of corresponding freeway lag vehicle for ramp vehicle i when vehicle i passed the fiducial mark j ,
 $X_{lead i}(d_j)$: Location of corresponding freeway lead vehicle for ramp vehicle i when vehicle i passed the fiducial mark j ,
 $\dot{X}_{ri}(d_j)$: Velocity of ramp vehicle i when it passes the fiducial mark j ,
 $\dot{X}_{flag i}(d_j)$: Velocity of the corresponding freeway lead vehicle i when vehicle i when it passes the fiducial mark j ,
 $\ddot{X}_{ri}(d_j + D)$: Acceleration rate of ramp vehicle i at location $d_j + D$,

The relevant R -square value was 0.566. A weakness of the proposed model is that it was calibrated with a limited amount of field data. In addition, the ramp merging position was found not to depend on any traffic parameter, which is controversial with common expectations and requires further examination.

Research conducted along the Tokyo Metropolitan Expressway in Japan (Sarvi et al., 2002) has focused on modeling ramp vehicle acceleration-deceleration behavior during the merging process in congested conditions. This methodology also, uses the stimuli-response equation to model the acceleration-deceleration behavior. In their research they introduce three stimuli to evaluate the ramp vehicle response. These are the relative speed regarding the freeway leader, the relative speed regarding the freeway lag vehicle and the spacing regarding the freeway leader. The hypothesized expression of the ramp vehicle acceleration-deceleration behavior of a ramp platoon leader entering the freeway is given as:

$$\begin{aligned}
 a_R(t+T) = & a_0 + a_1 \frac{V_R^m(t+T)}{[X_{Flead}(t) - X_R(t)]^4} [V_{Flead}(t) - V_R(t)] \\
 & + a_2 \frac{V_R^m(t+T)}{[X_R(t) - X_{Flag}(t)]^2} [V_R(t) - V_{Flag}(t)] \\
 & + a_3 \frac{1}{[X_{Flead}(t) - X_R(t)]^3} \{S(t) - f[v(t)]\}
 \end{aligned} \tag{2.2}$$

Where:

- $a_R(t+T)$: Acceleration rate of the ramp vehicle at time $t+T$ (m/s^2)

$X_R(t)$:	Location of the ramp vehicle at time t (m)
$X_{Flead}(t)$:	Location of the freeway lead vehicle at time t (m)
$X_{Flag}(t)$:	Location of the freeway lag vehicle at time t (m)
$V_R(t)$:	Speed of the ramp vehicle at time t (m/s)
$V_{Flead}(t)$:	Speed of the freeway lead vehicle at time t (m/s)
$V_{Flag}(t)$:	Speed of the freeway lag vehicle at time t (m/s)
$S(t)$:	Spacing between the ramp vehicle and the freeway leader vehicle at time t (m) ($X_{Flead}(t) - X_R(t)$)
$f[v(t)]$:	Desired spacing as a function of speed (m)
T :	Time lag or driver reaction time (s)

Although the data collected were not enough to cover all geometric conditions, they were used to calibrate the acceleration models. Two sets of models were investigated, linear and non-linear acceleration models, and these were proven to be equally significant.

Sarvi and Kuwahara (2005) have also developed an acceleration-deceleration model for the lag vehicle that approaches the merge area from the freeway under congested flow. They investigated the lag vehicle behavior in terms of its relative speed and spacing with its corresponding ramp and freeway lead vehicles. In their method, they used a non-linear specification to the stimuli-response equation.

Field data were collected through videotapes and image processing techniques during congestion periods. Based on the data, the lag vehicle has higher speed than the ramp vehicle in the beginning of the acceleration lane, but the lag vehicle either decelerates (to accommodate the merging) or the ramp vehicle accelerates (to force the merging). Next, the vehicle continues to accelerate to reach the leader vehicle. The leader and ramp vehicles have higher speeds than the lag vehicle.

The modeling of the lag vehicle is built upon previous work for modeling the ramp vehicle merging (Sarvi *et al.*, 2002). The main stimuli identified are the relative speed and spacing between the lag vehicle and its leading and ramp vehicles. The lag vehicle acceleration-deceleration behavior is given by the following expression:

$$\begin{aligned}
a_{Flag}(t+T) = & a_0 + a_1 \frac{V_{Flag}^m(t+T)}{[X_{Flead}(t) - X_{Flag}(t)]^{l_1}} [V_{Flead}(t) - V_{Flag}(t)] \\
& + a_2 \frac{V_{Flag}^m(t+T)}{[X_R(t) - X_{Flag}(t)]^{l_2}} [V_R(t) - V_{Flag}(t)] \\
& + a_3 \frac{1}{[X_{Flead}(t) - X_{Flag}(t)]^{l_3}} \{S(t)_1 - f[v(t)]\} \\
& + a_4 \frac{1}{[X_R(t) - X_{Flag}(t)]^{l_4}} \{S(t)_2 - f[v(t)]\}
\end{aligned} \tag{2.3}$$

Where:

$A_{Flag}(t+T)$:	Acceleration rate of the freeway lag vehicle at time $t+T$ (m/s^2)
$X_R(t)$:	Location of the ramp vehicle at time t (m)
$X_{Flead}(t)$:	Location of the freeway lead vehicle at time t (m)
$X_{Flag}(t)$:	Location of the freeway lag vehicle at time t (m)
$V_R(t)$:	Speed of the ramp vehicle at time t (m/s)
$V_{Flead}(t)$:	Speed of the freeway lead vehicle at time t (m/s)
$V_{Flag}(t)$:	Speed of the freeway lag vehicle at time t (m/s)
$S(t)_1$:	Spacing between the freeway lag vehicle and the freeway leader vehicle at time t (m) ($X_{Flead}(t) - X_{Flag}(t)$)
$S(t)_2$:	Spacing between the freeway lag vehicle and the ramp vehicle at time t (m) ($X_R(t) - X_{Flag}(t)$)
$f[v(t)]$:	Desired spacing as a function of speed (m)
T :	Time lag or driver reaction time (s)
a_0, a_1, a_2, a_3, a_4 :	Parameters
m, l_1, l_2, l_3, l_4 :	Parameters

This acceleration model was calibrated through linear and non-linear regression. Even though the non-linear model has greater R-sq value than the linear model, this difference was not significant, thus the linear model is sufficient for replicating the vehicle interactions.

Sarvi et al., (2000) developed a simulation program that was used for calibrating and validating the ramp vehicle acceleration model (Sarvi et al., 2002) and the lag vehicle acceleration model (Sarvi and Kuwahara, 2005), in conjunction with field measurements. In both cases the authors compared the vehicle trajectories from simulation data and the field data and it was shown that there is agreement between the two trajectories.

Kesting et al. (2007) presented a car-following model that includes the lag vehicle in the decision-making process and it is focused on modeling the acceleration. Safety constraints are also considered in the lane changing decision. The utility of a lane changing increases if the gap with the lead vehicle increases; however, if the speed of the lead vehicle is lower, then the subject vehicle may decide to stay on the present lane. They proposed a lane changing utility function that considers the difference in the accelerations (or decelerations) after the lane changing. For example, higher acceleration on a given lane suggests that this is closer to the “ideal” acceleration on an empty road; thus, it is more appealing to the driver. Another important feature of the proposed model is that it considers a “politeness” factor, which denotes in essence the (dis-)advantage of the lag vehicle (degree of cooperativeness). Moreover, the model considers a safety threshold which guarantees that after the lane change the deceleration of the follower will not exceed a given safe limit.

Examination of the lane changing rate through simulation showed that this primarily depends on the politeness factor. The politeness factor is an important model parameter, however, the proposed model represents only the last decision of whether to change lanes or not. Thus, information related to the decisions prior to the final lane-changing step, is not provided. Lastly, it is suggested that varying the safety threshold changes the “critical” lane change and this could further affect the breakdown probability.

Modeling Gap Acceptance for MLC

During the past 20 years, research has been involved with the study of gap acceptance during the merging process. Michaels and Fazio (1989) developed a freeway ramp merging model based on driver behavior. The concept of the model is that ramp drivers accept a gap based on an angular velocity. Michaels and Fazio note the continuous process of acceleration and gap-acceptance, and they distinguish several discrete tasks during the merging maneuver.

These are (1) the ramp curve tracking, (2) the steering transition from the ramp to the acceleration lane, (3) acceleration, (4) gap search, and (5) steering transition from acceleration lane to freeway or abort. During the gap search task the angular velocity is defined as the first order motion vector relative to the ramp driver and it is estimated as:

$$w = k(V_f - V_r)/l^2 \quad (2.4)$$

Where:

w :	Angular velocity (rad/sec)
V_f :	Freeway vehicle speed (ft/sec)
V_r :	Ramp vehicle speed (ft/sec)
l :	Distance separation (ft)
k :	Lateral offset (ft)

The angular velocity may have three different values, depending on the relative velocity and the distance. When the speed of the ramp vehicle is greater than the speed of the freeway vehicle (angular velocity is negative), this is an opening condition, and the ramp driver can merge as long as there is sufficient gap from the lead vehicle. When the speed of the ramp driver is less than the speed of the freeway driver (angular velocity is positive), this is a closing condition, and the merging decision depends on the angular velocity of the following vehicle, as long as the ramp vehicle is always behind the lead vehicle over the whole segment of the change speed lane. The third situation occurs when the relative speed and distance generate angular velocity below the threshold of 0.004 rad/sec (angular velocity is zero). An important hypothesis made, is that the merging maneuver can be an iterative process under congested conditions, where the ramp vehicle accelerates and searches for a gap iteratively, until its speed reaches that of the freeway.

In their model, they also incorporated the ramp curvature and the gap distribution function of the freeway traffic. Under heavy traffic conditions it was found that: (1) the median angular velocity is consistent with the literature, (2) drivers tend to decrease their speed between

successive accelerations as they are in a gap search process and not in speed control, and (3) the probability of merging increases with successive trials. Based on the proposed model, the authors present a procedure for estimating the length of the acceleration lane to provide adequate gaps. These findings indicate that the length is independent of freeway volume over a range of 1,200 to 2,000 pcphpln and that 650-800 ft is a sufficient lane length to ensure 85% or more merging opportunities for ramp drivers (for most used ramp design speeds). The proposed model however does not consider the interactions between the merge vehicles and the freeway vehicles as it assumes that the merging traffic has no influence on the mainline traffic.

Kita (1993) examined the merging behavior on an on-ramp section in the case where the merging vehicles are running slower than the through vehicles. The author developed: (1) a gap acceptance model that describes the merging behavior based on the merging probability and (2) a method to relate the safety level in a merging section with road and traffic characteristics.

The gap acceptance model (only sections with parallel acceleration lanes and not tapered were used) was based on a binary logit model of “accept” or “reject” choices of a sequential gap choice process. This model also considers the influence of the merging lane length on the driver’s decision process. The two alternative choices are formulated as:

$$P_a = \frac{1}{1 + \exp[-(U_a - U_r)]} \quad (2.5)$$

$$P_r = 1 - P_a$$

Where:

P_i : Probability that a driver chooses the alternative i
 U_i : Deterministic part of the drivers utility to the alternative i
 i : Alternatives (i = a: accept; i = r: reject)

and,

$$U_a - U_r = \theta_0 + \sum_{j=1}^J \theta_j x_j \quad (2.6)$$

Where:

x_j : Explanatory variables

θ_j : Parameters

($j = 1, \dots, J$)

Data from a three-lane freeway and one-lane ramp merging section were used for the model calibration. The data included measurements of speed, gap length, and merging position of each vehicle (distance from the merging nose to the point where the vehicle performs the merging maneuver). The first gap is defined as the time difference between the time when the merging vehicle reaches the merging nose and the follower vehicle reaches the merging nose. The second gap is defined as the time headway between the first vehicle and the second vehicle in the through traffic when the first vehicle reaches the same position as the merging vehicle. Cases where the through vehicle would change lane to avoid a conflict with the merging vehicle were excluded from the analysis. Additionally, when multiple merging occurred, only the data of the first merging vehicle were considered.

The explanatory variables selected for the model calibration are the gap length (sec), the remaining distance of the acceleration lane (m), and the relative velocity of the merging vehicle to the corresponding through vehicle (m/sec). The resulted goodness-of-fit measure was considered satisfactory ($\rho^2 = 0.785$).

Kita also developed models for the distribution of the merging position and the time-to-collision after merging, depending on the acceleration lane length. A case study to test the effect of the acceleration lane length on the distribution of time-to-collision was also developed. It was shown that the probability of a vehicle merging into a dangerous gap with shorter time-to-collision decreases when the acceleration lane length is longer.

Ahmed et al. (1996) developed a lane changing model which captures the gap acceptance process using discrete choice models. Lane changes were categorized as mandatory (MLC) and discretionary (DLC). A driver that needs to perform an MLC may either respond immediately or delay. This depends on the remaining distance, number of lanes to cross, and traffic density. If the driver does not respond to an MLC situation (or MLC does not apply), then he/she decides whether to consider a DLC or not, and its satisfaction with the current lane is evaluated. This decision depends on speed differences, deceleration, heavy vehicle presence and presence of ramps. Ahmed *et al.* developed a desired lane choice model (for both MLC and DLC) when both the adjacent lanes are candidate lanes. The explanatory factors are the speed differentials, deceleration, heavy vehicles, ramp presence and need for mandatory response. The last parameter forces the vehicles to perform an MLC should they be in this situation and they postpone the response.

The developed model was applied to the case of merging (MLC case). The gap acceptance model presented by Ahmed et al. (1996) addresses issues of heterogeneity and state dependence. The heterogeneity in the driver population was captured by introducing a random term in the critical gap specification, which varies across different components of a gap for the same individual, across different gaps for the same individual and across individuals. The lane changing model is assumed to be binary logit. The probability that a lane changing takes place given a gap is acceptable depends on several explanatory variables such as the time delay (since the gap searching process began), the remaining distance to the point where the lane change must be completed, the lag relative speed and a first gap dummy (captures the initial hesitation of the drivers to merge as soon as they appear at the beginning of the acceleration lane). The model formulation estimates both the lead and lag gap parameters separately. The lead critical gap was

found to be insensitive to traffic conditions, whereas the lag critical gap was found to be a function of the relative speed, remaining distance to the point at which the lane changing must be complete, and whether the gap is the first one considered or not. Ahmed et al. research captures the structure of the decision process and it also accounts for the stochasticity in driver behavior, but it does not capture any inter-dependence relation between the subject vehicle and the freeway vehicles.

Kita (1999) modeled the interactions between the merging vehicle and the through vehicle on on-ramp merging sections, using game theory. These interactions occur when the freeway through vehicle on the shoulder lane, changes lane to accommodate the merging maneuver of the ramp vehicle. Giveaway behavior occurs when traffic conflict with a merging vehicle is likely to happen, and it deals with low-speed merging where the speed of the merging vehicle is lower than that of the through vehicle. This study supplements a previous study performed by the author (Kita, 1993) which dealt with the influence of the freeway through vehicles to the merging behavior of the ramp vehicles. The interaction is modeled as a zero-sum non-cooperative game, where each driver chooses their best action considering the forecast of the other drivers, and its validity is tested through field data. Kita (1999) considers only the merging and the through vehicles as their interaction is the most dominant, but their behavior may affect the surrounding vehicles as well. It is also assumed that the number of games is one for each of the through vehicles in conflict and these games are independent. The game can be characterized as non-cooperative (the drivers cannot exchange any information) with perfect information (both drivers know the situation that the other driver is facing). By solving for the equilibrium condition the model derives the merging probabilities of a merging vehicle and the giveaway probabilities of a through vehicle.

Even though the merging vehicle may monitor the traffic conditions in a much wider area, the model estimates the payoff functions (utility functions) for both merging vehicle and through vehicle based only on their position and speeds relative to the neighboring vehicles, but it indirectly accounts for the influence of the adjacent through lane in the equilibrium solution. The concept behind this model is based on the assumption that the driver selects the action with the lower risk level, where the risk is the time to collision (TTC). However, this assumption is oversimplified and unrealistic, as it does not account for other factors such as the presence of the leader in the through lane that creates unsafe conditions for merging directly.

Kita et al. (2002) presented an improved giveway behavior model based on game theory. Kita et al. developed a method to estimate the payoff functions of merging and through vehicles without any information about equilibrium selection (which is rather difficult to estimate), and then analyzed the merging and giveway behavior by using the estimated method. In their analysis, the merging-giveway behavior is described by the through vehicle that gives way and the merge vehicle that merges in front of the through vehicle. In this situation, both vehicles attempt to take best action by forecasting the other's behavior. This behavior is modeled as a two-person non-zero-sum non-cooperative game under complete information. The actions of the merge vehicle are either merging or passing up the specific gap and the actions of the through vehicle are either to go with giveway or without giveway. The game matrix is defined as:

Table 2-1. Game matrix between freeway through vehicle and merging vehicle (source: Kita et al., 2002)

Merging vehicle action	Through vehicle actions	
	Go with giveway	Go without giveway
Merge	(F_{11}, G_{11})	(F_{12}, G_{12})
Pass up	(F_{21}, G_{21})	(F_{22}, G_{22})

In this method a set of probabilities is assigned to each action. If the probability of the merge vehicle merging is p and the probability that the through vehicle goes with giveway is q , then the expected payoffs of the merge driver ($EF(p,q)$) and the through driver ($EG(p,q)$) are:

$$\begin{aligned} EF(p,q) &= p \cdot \{q \cdot F_{11} + (1-q) \cdot F_{12}\} + (1-p) \cdot \{q \cdot F_{21} + (1-q) \cdot F_{22}\} \\ EG(p,q) &= p \cdot \{q \cdot G_{11} + (1-q) \cdot G_{12}\} + (1-p) \cdot \{q \cdot G_{21} + (1-q) \cdot G_{22}\} \end{aligned} \quad (2.7)$$

Thus, the best response of a driver, which is the probability that maximizes their expected payoff under the probability chosen by another driver, can be obtained from the derivative of the equations above and by checking if it is positive or negative. The equilibrium condition is the intersection point between the best responses of the drivers. The intersection point can be found if both drivers know the payoffs, however the external observer cannot estimate these deterministically. For this reason, Kita et al. consider that the equilibrium to be utilized is selected in a probabilistic manner. The probabilities that each type of best response is given are a function of the payoffs and also of factors that characterize the environment.

They examined three models for the payoff functions: a standard Time-To-Collision (TTC) model, a log TTC model and a model that considers the influence of leading vehicles. The estimation results showed that the model's capability of estimating the probabilities of equilibrium selection are fairly good, and can be used for the analysis of phenomena with strong interactions. This model however does not consider a minimum safe gap between the vehicles. Another limitation is that it does not account for the fact that the merging vehicle will slow down and stop at the end of the acceleration lane if it cannot merge safely. Also, it is assumed that all vehicles travel at a constant speed, with no provision for slowing down for the through vehicle when staying in the through lane. Lastly, it is assumed that the merging vehicle does not take any action to improve its merging position.

Goswami and Bham (2007) studied the gap acceptance behavior using the NGSIM data, along I-80 in Emeryville, California. Their focus was to obtain statistical distributions for the accepted and rejected gaps (and therefore, the critical gaps) in MLC maneuvers. Their motivation to study the distribution of acceptable gaps derives from the fact that the minimum acceptable gap does not represent the critical one, but only the gap acceptance behavior of an aggressive driver.

The data consisted of vehicle trajectories between an on-ramp and an off-ramp, under both uncongested and congested conditions. They examined the vehicle trajectories and considered vehicle interactions to occur when their distance is 250 ft or less. The Gamma and Lognormal distributions were tested for the (lag and lead) accepted gaps, and it was found that in some occasions the gaps are Gamma-distributed, while in some others they are Lognormal-distributed. They also used both deterministic (cumulative frequencies, acceptance curve) and stochastic methods (maximum likelihood, logit, probit) for estimating the critical gaps and conclude that the results from the logit and probit methods fit best to the data. Analysis of the critical gaps as a function of the location of lane changes indicates that in uncongested conditions the critical gaps (from the shoulder to the adjacent lane) are smaller than in congested conditions.

Zhang and Kovvali (2007) used the NGSIM data as well, to develop a gap acceptance model for the mainline vehicles. They considered the mandatory lane changes (MLC) but only from the vehicles exiting the freeway from the off-ramp at the study area. They evaluated 24 explanatory variables for the gap acceptance model, among these are: speeds, accelerations, vehicle types, etc., for the subject vehicle and also the lead and lag freeway vehicles. Two variables were also introduced, that are MLC-related, and these are the number of lane changes required to exit from the off-ramp and the distance to the MLC point.

Comparison between accepted gaps in MLC and DLC showed that these are statistically different (drivers in MLC situations select smaller gaps than in DLC). It was also found that the gap size decreases with increasing number of MLC, and that there is correlation between the acceptable time gaps and the distance to the MLC point (reveals drivers' urgency to change lanes). They also showed a correlation between the vehicle size and the accepted gap between the subject and the lag vehicles, (i.e., heavier vehicles accept larger gaps). Moreover, relative speeds were found to have little effect on acceptable gaps in MLC. Examination of the accelerations showed that the accepted distance gaps are smaller with higher subject vehicle accelerations, and that relative accelerations do not affect gaps significantly. Regression models of gap acceptance for both MLC and DLC were developed, however the regression coefficients are 0.495 and 0.389 respectively, which shows that there are still other unidentified factors that influence the gap acceptance process.

Integrated Models for MLC

Recent studies have developed models incorporating acceleration decisions to the merging models. Ahmed (1999) developed a lane changing model and an acceleration model to describe merging behavior under congested traffic. The structure of the lane changing model is presented in Figure 2-1. The lane changing process is described in three-steps through discrete choice framework: a decision to consider a lane changing, choice of a target lane and acceptance of gaps in the target lane.

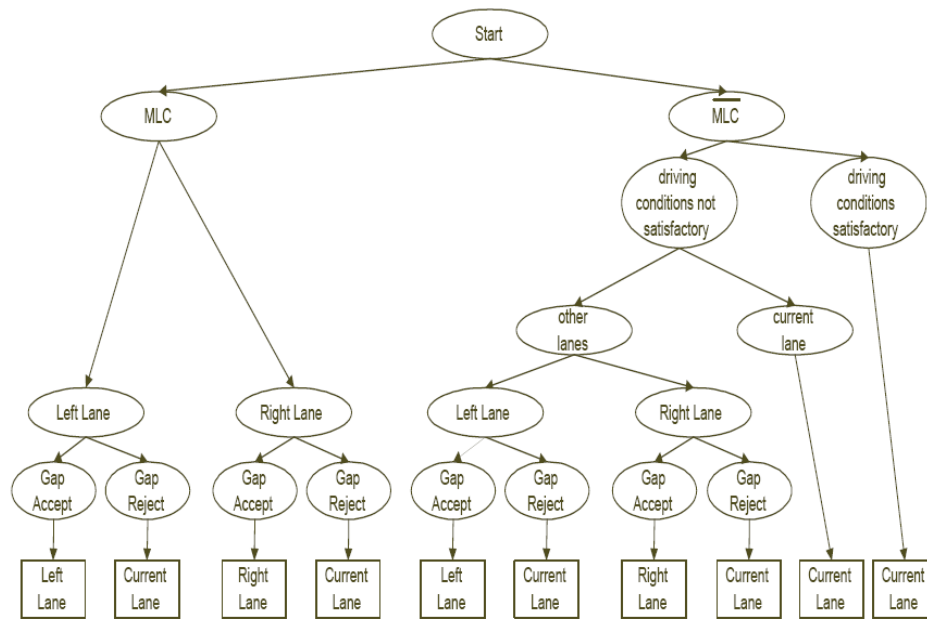


Figure 2-1. Lane changing model structure proposed by Ahmed (1999).

Ahmed (1999) proposed a lane changing model for uncongested conditions and a forced merging model for congested conditions based on his previous work (Ahmed, 1996). The lane changing model includes the lane selection model and the gap acceptance model.

Ahmed introduces the term “courtesy yielding” of the lag vehicle and “forced merging” of the subject vehicle to describe the proposed forced merging model. The merging vehicle evaluates the traffic environment in the target lane continuously, to decide whether to merge in front of the lag vehicle. The merging vehicle also communicates with the lag vehicle to check whether his/her right of way is established. If both of these occur, then the vehicle initiates a forced merging. If not, then the vehicle continues this process at the next time interval. Using a binary logit model, the probability of switching from the “start a forced merging state” to the “do not start a forced merging state” is modeled. Explanatory variables are the lead relative speed when the lead vehicle is slower, the lag relative speed, the remaining distance to the point that

the merging must be completed, the delay, the sum of lead and lag gaps, and the presence of heavy vehicles.

An important addition of Ahmed to the acceleration model was to include two components: the car-following model and the free-flow acceleration model. Ahmed defined a headway threshold to differentiate between the car-following regime and the free-flow regime. Another improvement of the acceleration model proposed by Ahmed (1999) was that he relaxed the assumption that the car-following stimulus is a linear function of the lead vehicle relative speed and used the density in front of the subject vehicle to capture the impact of traffic conditions. However, this model does not capture explicitly the impact of the lane changing decisions on the acceleration decision.

Toledo (2003) developed an integrated driver behavior model that captures lane changing and acceleration behaviors. The method is based on short term goals and plans. Drivers that target a lane change but cannot change lanes immediately, choose a short-term plan, and adapt their acceleration behavior to facilitate the lane changing. The model's structure searches for interdependencies between the different decisions of lane changing and acceleration. The model considers four levels of decision-making: target lane (lane choice), gap acceptance (lane changing), target gap (gap choice) and acceleration.

Toledo introduces three mechanisms that allow capturing interdependencies between the various decisions. These are causality, unobserved driver/vehicle characteristics and state dependency. The causality captures the effect of lower level choices on higher level decisions, because, the lower level choices are modeled conditional on those made at higher levels (e.g. the acceleration is conditional on the short-term plan). This was done by introducing variables that capture the expected maximum utility (EMU) of the alternatives at the lower level in the

specification of higher-level choices. A driver/vehicle specific variable was introduced in the model to capture correlations between observations obtained from a given driver. Finally, the state dependency mechanism aims in re-evaluating and potentially modifying the short-term goals and plans due to changes in driving conditions. This also addresses the fact that different combinations of short-terms and plans may result at the same observed conditions.

The target lane model integrates MLC and DLC into the same utility function for each target lane, rather than considering separate utility functions (Ahmed, 1999). The conceptual structure of the model is illustrated in Figure 2-2. Toledo integrated the two lane changing situations to capture potential trade-offs between mandatory and discretionary considerations.

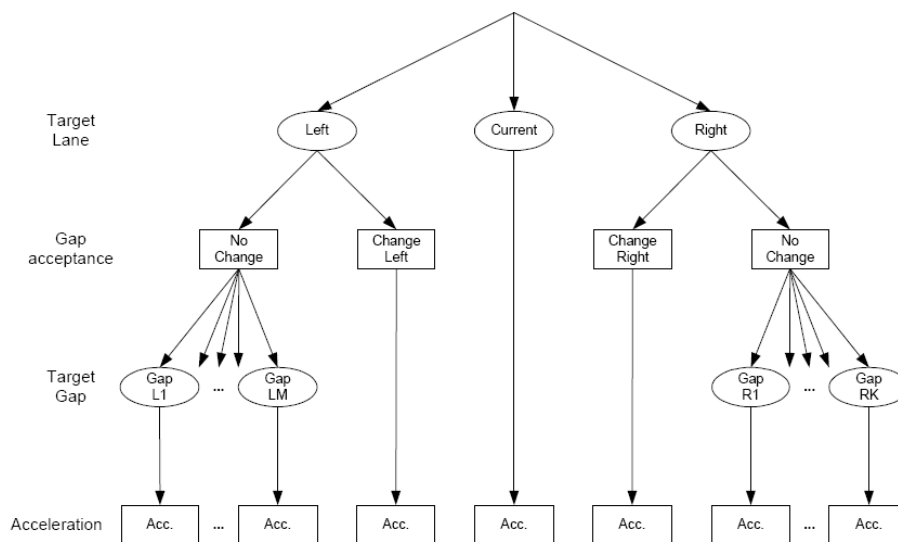


Figure 2-2. Lane changing model structure proposed by Toledo (2003).

The gap acceptance model captures the decision whether to change lanes immediately using the adjacent gap, conditional on the target lane choice. Explanatory variables for this model are the subject's speed, the relative speeds with respect to the lead and lag vehicles, the traffic density and the urgency of the lane changing. If the adjacent gap is rejected the driver does not change lanes and he is assumed to create a short term plan by choosing a target gap on

the target lane. The driver chooses between the adjacent, the backward and forward gaps. The explanatory variables affecting the utilities of each gap are the gap size, the gap trend, the subject's relative speed, and the distance to the point where the lane change must complete.

Three acceleration models were developed: the stay-in-the-lane acceleration, the acceleration during a lane changing (when the adjacent gap is accepted) and the target gap acceleration (when the driver does not change lane immediately). Additionally, two driving regimes are considered, depending on whether the operations are constrained or unconstrained. The stay-in-the-lane acceleration model is based on the model developed by Ahmed (1999). The constrained and unconstrained driving regimes assume car following and free-flow behaviors, respectively. For the lane changing acceleration model it is assumed that the driver determines the acceleration by evaluating the relations with the target lane leader. For the target gap acceleration model, the driver constructs and executes a short-term plan which depends on the target lane and the target gap choices. If unconstrained, the driver targets a desired position with respect to the target gap, which would allow the lane change to be performed. In this case the stimulus is the difference between the vehicle's desired and current position.

Although the proposed integrated model incorporates many different features and accounts for drivers' planning capabilities, behavior-related data were not used for the model validation. In addition, there is no accountability for lane changing during congested conditions, where courtesy yielding and even forced maneuvers take place.

Choudhury et al. (2006, 2007) present a lane changing model for merging and weaving that considers four levels of decision making process: normal gap acceptance, decision to initiate courtesy merging, decision to initiate forced merging, and gap acceptance for courtesy and forced merging. The structure of the proposed model is given in Figure 2-3.

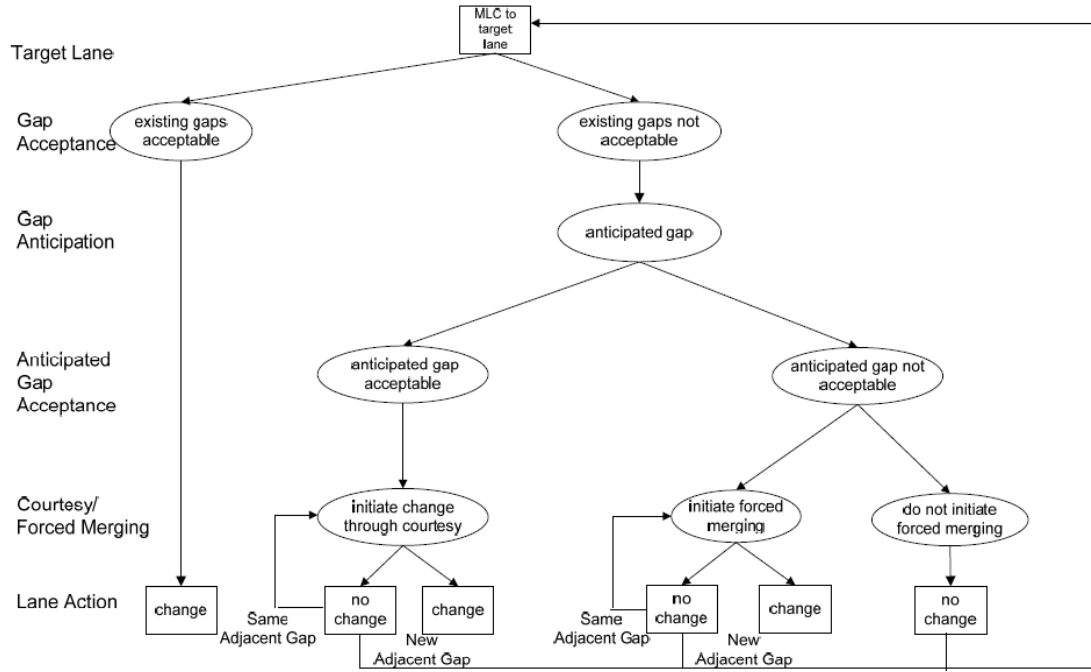


Figure 2-3. Structure of proposed model by Choudhury et al. (2007).

The data collected for this model are part of the Federal Highway Administration (FHWA) Next Generation Simulation (NGSIM) project. The data include vehicles' trajectories (position, acceleration and speed) along the Interstate I-80 in Emeryville, California, during transition to congestion and congested conditions. Observations of the lead, lag and the subject vehicle were recorded in a second-by-second basis. The distributions of the relative speeds and gaps show that when a gap is accepted, the subject vehicle is traveling slower than the lead vehicle and faster than the lag.

For the gap acceptance model, a gap is accepted if it is greater than the critical gap, which is modeled as a random variable following lognormal distribution.

$$\ln(G_{nt}^{ig}) = \beta^{ig^T} * X_{nt} + a^{ig} * u_n + \varepsilon_{nt}^{ig} \quad (2.8)$$

$g \in \{lead, lag\}, i \in \{normal, courtesy, forced\}$

G_{nt}^{ig} : Critical gap g of individual n at time t for merge type i ,

X_{nt} : Vector of explanatory variables,

β^{ig^T} : Corresponding vector of parameters that depend on the merge type,

ε_{nt}^{ig} :	Random term for gap acceptance for merge type i of individual n at time t ,
u_n :	Driver-specific random term,
a^{ig} :	Coefficient of the driver-specific random term of gap g , and merge type i .

The model assumes that the driver must accept both lead and lag gaps in order to perform a lane change. Explanatory variables are the relative speed between the subject and lead/lag vehicles, the remaining distance to the MLC point and the acceleration of the lag vehicle. If the gaps are unacceptable the driver evaluates the speed, acceleration, and relative position of the freeway vehicles and anticipates a gap that will be available in a later time. If these gaps are still not acceptable, then the subject vehicle will consider initiating a forced merge. Variables that affect the decision to initiate a forced lane changing are related to the status of the merging driver (distance to the MLC point, delay (intolerance), and speed), the lag vehicle status (vehicle type, speed and acceleration), and the traffic conditions (congestion level and tailgating dummy).

Choudhury et al. (2007) recently extended their model by integrating drivers' acceleration and deceleration actions to facilitate their merging maneuvers. They incorporated three different acceleration models (Figure 2-4), which are: lane change acceleration and target gap acceleration (similar to Toledo, 2003), and initiated courtesy/forced merging acceleration. The lane change acceleration occurs when the existing gaps are acceptable and it is based on the relative speed with the leader. The target gap acceleration is performed when the subject vehicle seeks an improved position with respect to the lead and lag vehicles (can select forward, adjacent or backward gap). The initiated courtesy/forced merging acceleration seeks to obtain an improved position while in the subject lane, with respect to the lead and lag vehicles. These acceleration models are still under development and have not been finalized to this moment.

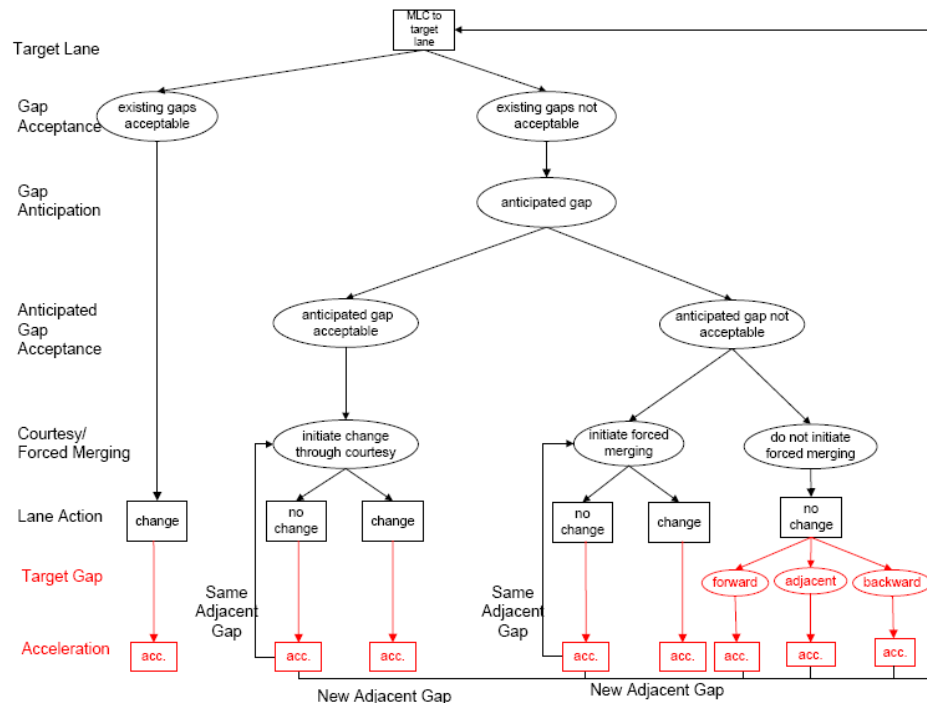


Figure 2-4. Extended model proposed by Choudhury et al. (2007).

Mandatory Lane Changing Models Used in Simulation Programs

Lane changing rules and models have been extensively used in microsimulation programs to provide a more realistic representation of traffic operations. Yang and Koutsopoulos (1996) presented the Microscopic Traffic SIMulator (MITSIM) where they implemented a rule-based lane changing model. They presented a merging model, separately from the lane changing model. The merging model is classified into: (i) priority-based merging and (ii) merging without priority, while the lane changing model distinguished between MLC and DLC lane changes. In contrast to other models, merging from on-ramps is modeled through the merging model and not through the MLC model. More specifically, the priority-based merging includes merging from on-ramps or dropped lanes to the freeway, and from minor to major streets, and the merging without priority includes merging downstream of toll plazas. They define that MLC occurs when vehicles have to change lanes to (i) connect to the next link on their path, (ii) bypass a lane

blockage, (iii) avoid entrance to a restricted use lane, and (iv) respond to LUS or VMS. DLC occurs when a driver wants to increase speed, or overtake a heavy vehicle, or to avoid the lane connected to an on ramp.

For the priority-based merging model, the merging vehicle checks whether there is an upcoming vehicle and executes the maneuver only if the projected headway gap is acceptable. If the headway gap is not acceptable, the vehicle either calculates the acceleration rate (by treating the freeway vehicle as leader) or stops at the end of the acceleration lane, depending on which case is the critical one.

In addition, the merging model incorporates a courtesy yielding parameter in case the vehicle decides to decelerate to create space for another vehicle to merge. This is done by assigning a probability of courtesy yielding to the drivers, and applying the deceleration rate calculated from the car-following model; however not enough details are provided about this process.

The lane changing algorithm in MITSIM (based on Gipps model) is implemented in three steps: (i) check the necessity of lane change and define its type (mandatory or discretionary), (ii) select desired lane, (iii) execute lane changing if gaps are acceptable. For DLC, the decision to change lane is based on traffic conditions on both current lane and adjacent lanes. The model introduces an impatience factor and a speed indifference factor, to determine whether the speed is low enough and the speeds at the adjacent lanes are high enough for considering a lane changing. A lane change is executed only if both the lead and lag gaps are acceptable. The critical gaps used in MITSIM are assumed to follow the lognormal distribution.

Hidas (2002) presented a lane changing and merging algorithm implemented in the simulator named Simulation of Intelligent TRANsport Systems (SITRAS). Key aspects of these

algorithms are the forced and cooperative lane changing modules, which are significant for modeling congested traffic conditions. The necessity of a lane change is evaluated in each simulation interval, and depending on the situation (turning movement, incident, end-of-lane, transit lane, speed advantage, queue advantage), it can either be essential, desirable, or unnecessary. Next, the feasibility of the lane change is examined, depending on the gap availability at the target lane. A lane change is considered feasible if (i) the deceleration/acceleration needed for the subject vehicle is acceptable, and (ii) the deceleration required by the potential follower is acceptable. An aggressiveness parameter is incorporated to the deceleration calculation, to differentiate between driver types.

When an MLC is warranted, the lane selection process is terminated. Hidas incorporated the driver courtesy in the case of forced lane changes. This concept deals with the reduction in acceleration required for the potential new follower to allow the subject vehicle to move to the target lane. Other important elements presented by Hidas (2002) with respect to the merging model, are:

- acceptance of shorter critical gaps than those that derive from the car-following model,
- implementation of acceleration in order for the subject vehicle to better position during the lane change,
- implementation of lane changing behavior for the right-lane freeway vehicles approaching the ramp merge, if ramp vehicles are present, in order to avoid any friction,
- application of lower deceleration when ramp vehicles try to merge into the freeway using very short gaps, instead of using large deceleration that could potentially disturb the freeway flow, and,
- application of the driver courtesy function only to congested traffic conditions.

In 2005, Hidas presented an updated version of SITRAS (renamed to ARTEMiS), for simulating lane changing and merging models under congested conditions. The objective of the lane changing model in ARTEMiS is to determine under which conditions a vehicle is allowed to

move into the target lane, and consider the issue that the drivers are willing to tolerate much shorter gaps when they can anticipate the actions of other drivers, and do not use the maximum but a moderate deceleration.

Data collected in the field showed that in congestion, lane changes occur at short gaps and that the accepted gaps are more closely related to the relative speed between the leader and the follower than to the absolute speed of the follower vehicle. It was also shown that when the leader is faster than the follower, the minimum accepted gap was constant, but if the leader is slower than the follower, the minimum accepted gap increases with the speed difference.

Analysis of gap acceptance led to the classification of lane changing maneuvers as free, forced and cooperative. Free lane changing occurs when there is no significant change in the relative gap between the leader and follower, which means that there is no interference between the subject and the follower vehicle. Generally, in a free lane change there is no interaction between the vehicles. Forced lane changes are associated with apparent change in the gaps before and after the merge point, i.e., the gap between the leader and the follower was either constant or narrowing before the merge and it widens after the merging vehicle enters. Thus, the subject vehicle forces the follower to decelerate. In essence, the subject vehicle plays an active role by initiating the merge, and the follower reacts to that action. In cooperative lane changes the gap between the leader and the follower is increasing before the entry point and it decreases afterwards, which indicates that the follower decelerates to allow the vehicle to merge. In cooperative lane changes, at first, the subject vehicle indicates its willingness to move to the target lane, then the follower acknowledges the situation and cooperates by slowing down, and eventually, the subject vehicle realizes that the follower gives way and when the gap is long enough, it merges.

Wang et al. (2005) present a model of freeway merging behavior that considers the acceleration and gap acceptance behavior. The authors introduce two plausible behaviors/reactions of the freeway traffic approaching the merge: cooperative lane changing (to allow vehicles to merge) and courtesy yielding (decelerate to create gaps). The following series of sub-models are introduced to capture the merging behavior and to develop the simulation model:

- Cooperation model: It captures the cooperative yielding behavior and the cooperative lane changing, that essentially facilitates the merging process by creating gaps for the ramp vehicles.
- Acceleration model: It captures the acceleration-deceleration decisions of the merging vehicle. It is influenced by the target gap on the freeway, the leading vehicle on the acceleration lane and the remaining distance to the end of the acceleration lane. They modeled the ramp vehicle's acceleration to reach the speed of the leading vehicle, as well as the deceleration of the vehicle based on the relative speed and gap with the leader. If the speed of the merging vehicle is very close to the speeds of the follower or the leader (small relative speeds), another acceleration model is employed which aims in creating larger lead or lag gaps. A parameter for the driver aggressiveness is also introduced. The model incorporates a maximum acceptable deceleration as an urgency, to prevent the merging vehicle from running into the vehicle in front or the end of the acceleration lane.
- Gap selection model: It is based on the speed of the merging vehicle and its position relative to the freeway leader and follower. The target gap is assumed to be the adjacent gap, unless different situations occur, such as a fast moving vehicle that overtakes the leader on the acceleration lane and takes the previous gap as its target gap, or a slow moving vehicle that chooses to take the following gap.
- Gap acceptance model: It is based on the game theory idea proposed by Kita *et al.* (2002) where the merging vehicle makes a decision considering the forecast of the other vehicles' actions and its own actions. The model calculates the acceptable lead and lag gaps as a function of the speed, merging driver's reaction time and maximum decelerations of the merging, the leader, and the follower vehicles, depending on their projected reactions to the merging process.
- Merge model: It captures the presence of an acceptable gap and the merging process. However, if the vehicle is reaching towards the end of the acceleration lane and an acceptable gap is not found then a merge failure is registered.

The model was tested through simulation and a sensitivity analysis was performed to evaluate how the parameters affect the merging process. The model was found to be sensitive to

the length of the acceleration lane and the average freeway flow. For long acceleration lanes and low speed on the freeway, the merging failures were fewer and there is a greater chance that a following gap will be chosen. The optimal acceleration lane length for smooth merging (accepting the adjacent gaps) was found to be approximately 100 meters (330 ft.). With longer acceleration lanes vehicles tend to take the following gaps and not the adjacent gaps. It was also found that the accepted lead and lag gaps decrease with increasing flows but these do not vary with increasing merging flows. The authors tested a range of values for the gap acceptance factor and the driver's reaction time and compared the derived outputs with field data from the literature; however, a direct calibration of the proposed model parameters was not performed.

CORSIM (Halati et al. 1997) distinguishes three types of lane changing: (i) mandatory, (ii) discretionary and (iii) anticipatory lane changes. Mandatory lane changes are considered in the following situations: (i) merging traffic entering on the freeway, (ii) lane changing for diverging traffic to exit the freeway, (iii) leaving a blocked lane due to an incident, (iv) vacating a dropped lane. In CORSIM, a lane change is performed if both lead and lag gaps are acceptable. The gap acceptance process involves a risk factor. More specifically, the model compares the acceptable level of risk (acceptable deceleration) for avoiding collision, between the potential follower and the merging vehicle. The acceptable risk factor depends on lane changing type, driver type, and urgency of lane changing.

In addition, vehicles initiate the merging as soon as they enter the acceleration lane. Merging vehicles' acceleration is determined by considering that it car-follows a stopped 'dummy' vehicle at the end of the acceleration lane and this is compared with the deceleration required to stop at that location. The minimum of the two decelerations is applied. CORSIM

also models the anticipatory lane changes of the freeway vehicles that give up the shoulder lane to avoid potential conflict and speed reduction caused by the merging traffic.

VISSIM applies a psychophysical model that presents critical gaps as thresholds depending on the relative speeds of the subject vehicle and the assumed leader and follower. Lane changing vehicles may accept progressively higher deceleration rates as an urgency to complete the merging maneuver. At the same time, the merging vehicles may cause the through vehicles to accept higher deceleration rates as the merging vehicle approaches the end of the acceleration lane. During lane changes the subject vehicle may accelerate to facilitate its maneuver, and there is provision for cooperation between the vehicles.

Merging Under Congested Conditions

Various researchers have contributed to the investigation and modeling of merging behavior during congested traffic conditions. Sarvi et al. (2002) performed research for modeling ramp vehicle acceleration-deceleration behavior during the merging process in congested conditions. Based on the field data collected at two ramp junctions along the Tokyo Metropolitan Expressway, Sarvi et al. observed that the merging behavior under congested conditions occurs on a one-by-one basis regardless of the length of the available gap (also referred to as zip merging or zipper effect). The authors do not make use of the gap acceptance methodology because previous research (Sarvi and Kuwahara, 1999) found that during heavy congestion, unstable or stop-and-go traffic flow appears to take place, and the gap searching and acceptance maneuvers do not occur. This zip merging behavior has been characterized also as turn-taking merging by Cassidy and Ahn (2005), who showed that the merging occurs in an almost one-by-one basis, and this ratio remains constant at each site, irrespective of the merge outflow. Furthermore, Sarvi et al. (2007) performed an analysis of macroscopic observations on driver behavior, and they showed that under congested conditions, the ratio of ramp flow over

the total flow does not affect the capacity of the merging segment. They further observe that the opposite occurs during merging under free flowing conditions, where the distribution of these two volumes is related to the easiness of the merging operation: i.e., all else held constant, fewer ramp vehicles suggests easier merging. Lastly, after examining the lane distribution they conclude that the shoulder lane is being under-utilized, i.e., the shoulder lane volume was approximately 1/3 of the median lane, and the ramp shoulder lane volume was half of the volume on the ramp median lane.

Using Instrumented Vehicles to Study Driver Behavior

Various studies have been conducted with the participation of subjects and the use of instrumented vehicles to study closely a variety of driver behavior-related issues. Researchers in psychology have deployed instrumented vehicles to study physiological responses of drivers and how these relate to the driver-vehicle-environment system (Helander, 1978). Measurement of the electrodermal response (EDR) and heart rate (HR) in the occurrence of various external factors showed that a vehicle merging in front of the subject vehicle may induce great difficulty in the driving task. Lane changing activity may have similar psychological implications. Recently, Chang et al. (2001) showed that driver's load in acceleration lane before merging is higher than the freeway section and that it was maintained after the completion of the merging maneuver.

Other researchers in the field of robotics and control theory have collected behavioral data using instrumented vehicles, aiming in modeling and predicting driver's maneuvers that can potentially be used in automated driver assistance systems and ITS applications (Salvucci et al. 2007; Hegeman et al. 2005; Oliver and Pentland, 2000; Pentland and Liu, 1999). In the same context, Shimizu and Yamada (2000) studied the effectiveness of the AHS (Advanced and cruise-assist Highway System) in merging behavior under non-congested conditions, using an

instrumented vehicle. Their results indicated that the system could result in smoother merging behaviors, given that the driver recognizes the traffic flow on the mainline in advance.

Traffic safety and driver performance is another research field where instrumented vehicles have been used. Such example is the 100-car naturalistic study performed by Virginia Tech's Transportation Institute, where the purpose was to collect pre-crash naturalistic driving data. Additional research performed by the 100-car naturalistic study (Hanowski et al. 2006), focused on the interactions between light and heavy vehicles. In their study, video cameras and other equipment were installed to one hundred light vehicles and the analysis entailed recording of each light vehicle-heavy vehicle interaction event. Sayer et al. (2007) performed a naturalistic driving study using 36 drivers in order to examine their engaging in secondary behaviors (conversation, grooming, cell phone use, eating/drinking, etc.) and to explore the effect of these behaviors on the driving performance. Horrey et al. (2007) have gone beyond exploring the effect of secondary behaviors on drivers' responses and they examined to which degree drivers are aware of these distraction effects (namely, the cell phone use).

Classen et al. (2007) used an instrumented vehicle and surveys to evaluate the safety effects of geometric improvements at intersections, on the driving ability of older drivers. Analysis of the data indicated that at the improved intersections the average speed was increased and also drivers made fewer errors compared to the unimproved intersections. Further comparisons between younger and older drivers indicated that older drivers make more mistakes than the younger ones, however, all drivers benefit from the geometric improvements.

In addition, a significant amount of research has been involved with the examination of microscopic traffic characteristics. Brackstone et al. (1999) performed a study using an instrumented vehicle for developing and calibrating models of driver behavior. The vehicle was

equipped with various sensors such as: optical speedometer, microwave radar which measures distances to the adjacent vehicles, and two video cameras (one rear-facing and one front-facing) with audio recording system. Information from all sensors was stored at a PC for further analysis. Seven subjects were used where each was instructed to follow another test vehicle. Analysis of the data showed that the front and rear gaps, and the time to collision (TTC) are important factors that affect lane changing decisions. Brackstone et al. also found two thresholds for TTC: one of 45 seconds above which a gap is almost always accepted and a second at about 20 seconds, below which a gap is almost always rejected. The authors hypothesize that there might be an intermediate threshold for which the decision for a lane change would mostly depend on lane and local flow and density, among other parameters. Lastly, in-vehicle interviews with a limited number of subjects were performed to investigate their perception of relative speed (denoting as “closing”, “constant” or “opening”).

Brackstone (2003) used an instrumented vehicle to collected data for a car-following study. He applied the same instrumented vehicle in this research which is relevant to the classification of drivers' attributes. Brackstone examined correlations between different indicators of driver personality/ experience and found that at low speeds, drivers with high externality (measures drivers feelings regarding locus of control and responsibility) will have high following distances, while drivers who score high on the sensation scale would have lower following distances. They did not conclude to anything similar at high speeds.

Recently, Wu et al. (2007) examined the effect of ramp metering on the driving performance of merging vehicles, using the instrumented vehicle described in Brackstone et al. (1999). More specifically, they examined whether ramp metering can reduce the stress of the merging vehicles and whether it can smooth traffic downstream of the merge junction. In

addition to the vehicle sensors, loop detector data were available on the freeway (upstream of the merge junction) and on the on-ramp. All data (in-vehicle, loop and video data) were used for the investigation of gap acceptance, speed at merge and merge location during the merge process. The subjects were instructed to follow both a merging route and a through route. Wu *et al.* performed three investigations: (i) the behavior of the through traffic, (ii) the behavior of the merging vehicles at the merge point, and (iii) the behavior of the freeway through vehicles upstream of the merge. The research finding showed that ramp metering has insignificant effect on the behavior of the through traffic (mean speed, acceleration, and time headway). It was also found that ramp metering resulted in increased lane changing activity and higher headways from the outside lane to the middle lane, which indicates a flow reduction upstream of the merge. Speeds and headways on the middle and median lanes were not found to be statistically different. Lastly, the effect of ramp metering on the merging traffic included increase of acceptable gaps, and reduction in merging speeds, which indicates easier merging conditions for merge traffic.

There are other studies as well that collected data using instrumented vehicles to establish microscopic driver behavior relationships. Cody *et al.* (2007) used instrumented vehicles to examine the gap acceptance decision making during left-turn maneuvers from an intersection. Ma and Andreasson (2007) also used an instrumented to collect car-following data on Swedish roads. The authors also developed a fuzzy clustering algorithm to distinguish between the different car-following regimes.

Henning *et al.* (2007) examined several behavioral and environmental indicators that predict drivers' intent to change lanes. Data collected from an instrumented vehicle include speed, acceleration/deceleration, yaw rate and inclination, eye movement, steering wheel position, pedal use and turn signal use, distance to the car in front and GPS positioning. Cameras

were also set to record 5 different views around the vehicle. The indicators considered for the lane change maneuver are the first glance to the left mirror, the turn signal and the actual lane crossing, all three of which were found in the data collected.

In concluding, instrumented vehicles have been widely implemented for data collection in transportation-related studies. By combining data from vehicle sensors (gear, acceleration, throttle, etc) in-vehicle cameras either facing the driver or the roadside environment or both, and loop detectors, researchers have gathered useful information for understanding and modeling driver behavior at the operational and also tactical level.

Although the use of instrumented vehicles can provide useful information about driver behavior, the experiments should be designed with care, and the results should be analyzed with caution, as research has shown that human behavior may change even if very subtle indication exists of being watched. Not only is this true, but it has been also shown that the behavior becomes more altruistic as people, and even some animals are being observed (Milinski and Rockenbach, 2007). This derives from the fact that by observing (or rather “snooping on”) other people, we actually work out how to behave in the future. Consequently, people (and also animals) try to deceive the observers in order to secure future gains (e.g., positive reputation). The authors further comment that:

Watchful eyes induce altruistic behavior and an ‘arms race’ of signals between observers and the observed.

Summary of Literature Review

According to the literature, capacity associated with breakdowns at freeway ramp merging segments is a stochastic variable, because the breakdown events can occur over a wide range of traffic conditions. It has been also shown that these breakdown events are the result of conflicts that occur during the merging process, when traffic moves towards congested conditions. For

example, Elefteriadou et al. (1995) and Yi and Mulinazzi (2007) discuss vehicle platoons; Kerner and Rehborn (1996, 1997) mention of vehicles “squeezing” on the highway. Further observations in the vicinity of ramp merges note that the consequence of these interactions between the on-ramp and the freeway vehicles may be for several vehicles to decelerate and cause other vehicles to reduce their speed as well, leading towards the occurrence of breakdown.

Merging behavior during complete congestion (queues on the freeway and the on-ramps) appears to follow the “zipper effect” or is described by taking turns (Cassidy and Ahn, 2005). This behavior could potentially be easy to model, given that the queue lengths are known.

The merging process has been studied to a significant degree in the literature, and the developed models are typically applied in microscopic simulators to provide a more realistic representation of traffic operations. Most of the MLC models are based on gap acceptance rules. Recent refinements of the models include the addition of the cooperative behavior of the freeway through vehicles (cooperative merging), and also the competition between freeway and ramp vehicles (forced merging). Recent research has also incorporated acceleration-deceleration decisions of the merging vehicle, to provide a more complete outlook of the merging process. Important parameters identified to affect drivers’ choices of acceptable gaps during the merging process pertain to traffic conditions, geometric attributes, relative speeds, and also individual driver characteristics (impatience factor, aggressiveness).

The merging process on freeway-ramp merging segments has been studied in a significant extent during the past twenty years, however many limitations are identified to date. For instance, decisions that occur during the merging process have been established by various researchers, but these have not been evaluated by actual drivers. As such, the effect of individual drivers’ characteristics on the decision-making process is still unknown. Generally, driver

behavior has been considered an important factor in the literature, but this has not been examined closely. This also means that there are no data showing if the merging process differs by driver's aggressiveness, e.g., if an aggressive driver makes different acceleration and gap acceptance decisions differently than a timid driver.

In addition, current research has included the effect of traffic conditions on the merging decisions, but has not studied the opposite; the impact of individual drivers' merging maneuvers on the overall traffic stability. This type of research could provide some answers concerning the breakdown events and the resulting capacity at freeway ramp merges. Thus, how the behavioral characteristics of drivers can trigger instabilities affect at a given freeway-ramp junction can give insights regarding the occurrence of a breakdown.

CHAPTER 3 BEHAVIORAL BREAKDOWN PROBABILITY METHODOLOGY

This chapter presents the methodological framework for the development of the breakdown probability model at freeway merges considering driver behavioral characteristics. First, the structure of the merging process with the respective decision-making steps is presented. Following that, the breakdown probability model is formulated, which accounts for the effect of driver interactions and merging maneuvers on the freeway operations.

Merging Model Structure

This section presents the proposed structure of the merging process. The conceptual framework of the merging process is illustrated in Figure 3-1.

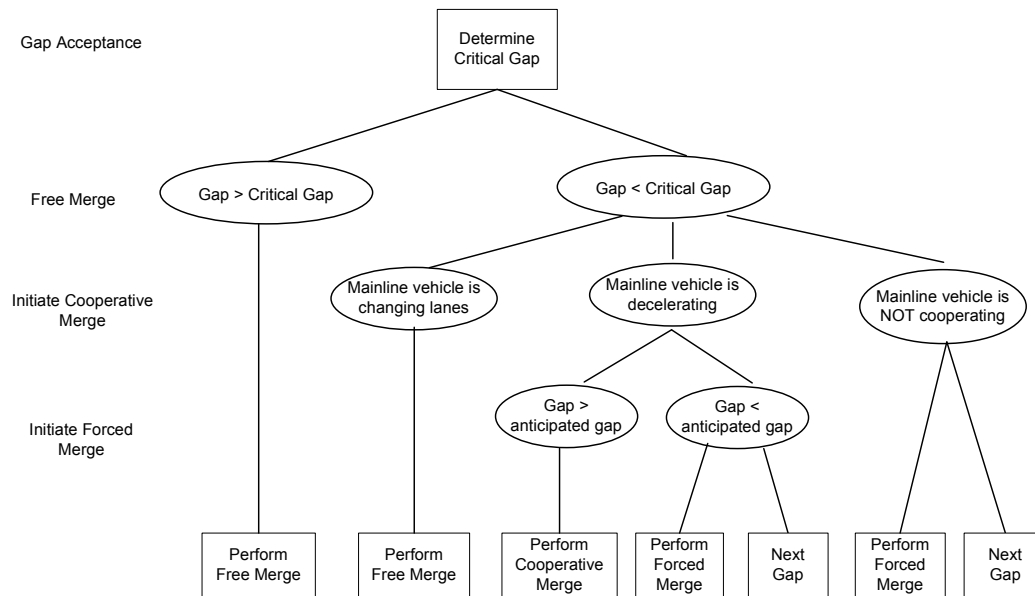


Figure 3-1. Conceptual description of merging process.

The conceptual merging process combines ideas from previous models in the literature (Toledo, 2003; Choudhury, 2007), with the data collected through this thesis. The model presents 4 levels of decision-making: gap acceptance, decision for free merge maneuver, decision to initiate cooperative merge, and decision to initiate forced merge maneuver.

As it is shown in Figure 3-1, the merging model is based on gap acceptance. The critical gaps depend on driver's aggressiveness, the traffic conditions and the geometry of each site. The critical gaps are typically the minimum acceptable gaps.

The gap acceptance model checks which gap is acceptable for merging. Each gap is defined by the lead and lag gaps in the shoulder lane, as depicted in Figure 3-2.

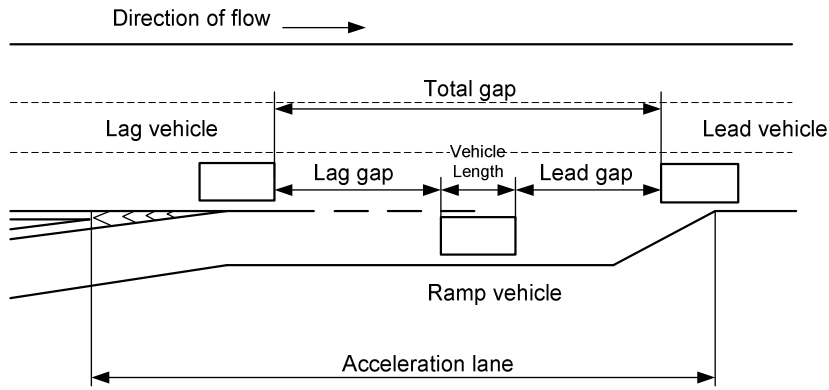


Figure 3-2. The lead, lag, and total gap.

The available lead, lag and total gaps are compared to the ramp driver's critical (i.e., minimum acceptable) gaps, and these are accepted if they are greater than the critical gaps. The critical gaps are assumed to follow a lognormal distribution to ensure their non-negativity.

$$\begin{aligned} \ln(G_R^{lead,i}) &= X_R^{lead,i} * \beta^{lead,i} \\ \ln(G_R^{lag,i}) &= X_R^{lag,i} * \beta^{lag,i} \end{aligned} \quad (3.1)$$

Or equivalently,

$$\begin{aligned} \ln(G_R^{total,i}) &= X_R^{total,i} * \beta^{total,i} \\ i &\in \{free, cooperative, forced\} \end{aligned} \quad (3.2)$$

Where, $X_R^{lead,i}$, $X_R^{lag,i}$ and $X_R^{total,i}$ are vectors of explanatory variables affecting the lead, lag and total critical gaps under the different types of merging maneuvers, respectively. $\beta^{lead,i}$, $\beta^{lag,i}$ and $\beta^{total,i}$ are the corresponding vectors of parameters. The gap acceptance model assumes

that both the lead gap and the lag gap or the total gap must be acceptable in order for the ramp vehicle to merge, under any merging maneuver. The probability of accepting a gap and performing any of the possible merging maneuvers is given by:

$$\begin{aligned}
 P_R(m^i) &= P_R((\text{accept lead gap})^i) \cdot P_R((\text{accept lag gap})^i) = \\
 &P_R(G_R^{\text{lead},i} > G_R^{\text{lead},cr,i}) \cdot P_R(G_R^{\text{lag},i} > G_R^{\text{lag},cr,i}) \\
 &\text{or} \\
 P_R(m^i) &= P_R(\text{accept total gap})^i \\
 i &\in \{\text{free}, \text{cooperative}, \text{forced}\}
 \end{aligned} \tag{3.3}$$

Assuming that critical gaps follow a lognormal distribution, the conditional probability that the lead gaps and the lag gaps are acceptable is given respectively by:

$$\begin{aligned}
 P_R(G_R^{\text{total},i} > G_R^{\text{total},cr,i}) &= P_R[\ln(G_R^{\text{total},i}) > \ln(G_R^{\text{total},cr,i})] = \\
 \Phi \left[\frac{\ln(G_R^{\text{total},i}) - (X_R^{\text{total},i} \cdot \beta^{\text{total},i})}{\sigma_{\text{total},i}} \right]
 \end{aligned} \tag{3.4}$$

Where $\Phi[\cdot]$ is the cumulative standard normal distribution.

If the gap is rejected, then the ramp vehicle needs to re-examine the situation, by evaluating the mainline lag vehicle's reaction. If the mainline vehicle initiates cooperation (decelerate or change lanes), the ramp vehicle may decide to accept the gap and merge. If the mainline vehicle is not willing to yield or its deceleration is not enough, the ramp vehicle may decide to initiate a forced merge.

The following sections present the basic elements of the three preliminary merging models in more detail.

Free Merge Model

This section presents the detailed free merge process. The structure of the proposed free merge model is illustrated in Figure 3-3.

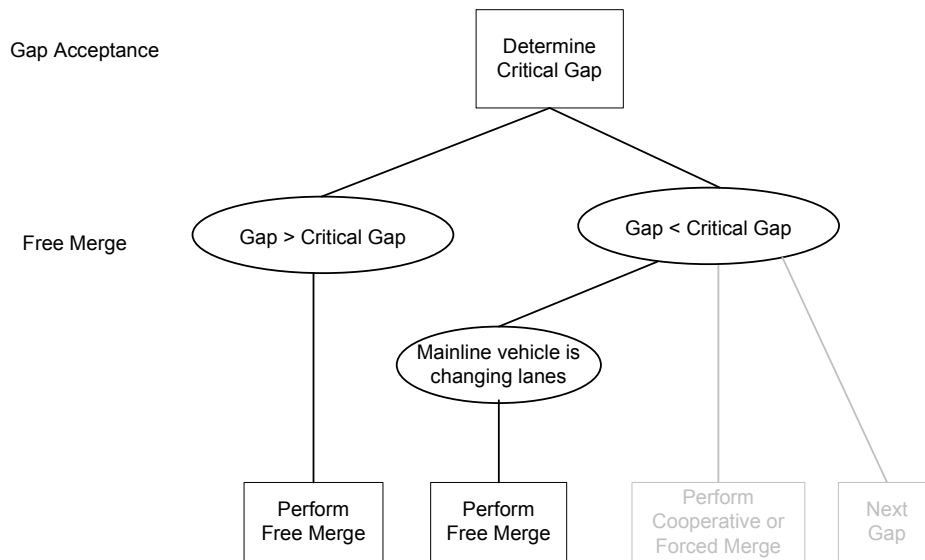


Figure 3-3. The free-merge model.

If the gap is larger than the critical gap, or if the freeway vehicle yields by changing lanes, then the ramp vehicle initiates a free merge. The critical gap is the minimum acceptable gap under free gap acceptance conditions. The critical gap is the critical total gap between the potential freeway lead and lag vehicles, as shown in Figure 3-2.

Cooperative Merge Model

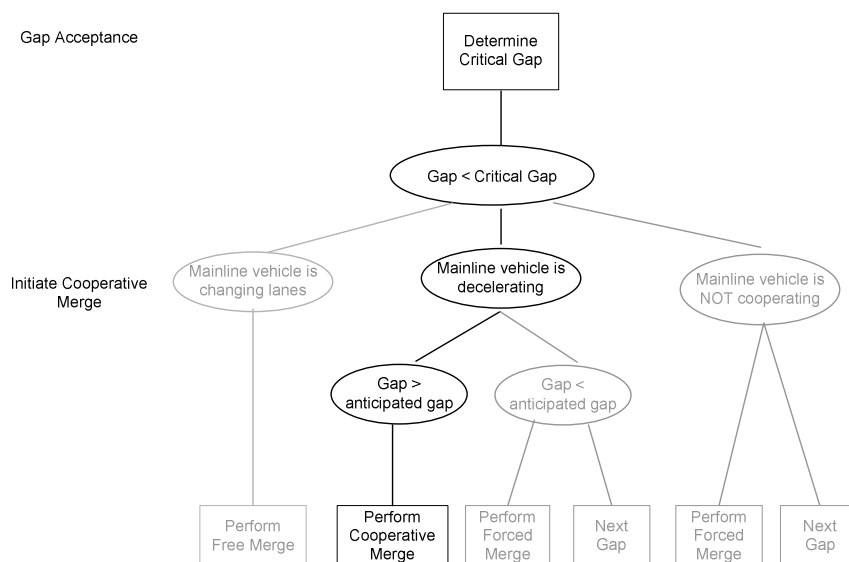


Figure 3-4. The cooperative-merge model.

During this decision level, both ramp and mainline lag vehicles need to evaluate the situation ahead. Frequently, a mainline vehicle that is approaching the on-ramp will evaluate whether it should change lanes or decelerate to make room for the ramp vehicle, or continue its course. If the freeway vehicle changes lanes, then the ramp vehicle will merge under free-merge conditions. However, if the freeway vehicle decelerates, then the ramp vehicle will evaluate the situation and depending on its perception of the mainline vehicle's actions, it will react by accepting the freeway vehicle's cooperation and merge.

The decision to accept the gap formed after the cooperation depends on whether the mainline vehicle is willing to decelerate or not. The freeway vehicle's willingness to decelerate (Hidas, 2005) may depend on several factors such as the driving experience, the freeway vehicle's degree of aggressiveness, the mental state of the driver (being in a hurry, disconcerted about other things, etc), the urgency of the maneuver as this is perceived by the freeway vehicle, and the downstream traffic conditions.

Given that the mainline vehicle slows down, the potential gap size increases; thus, the ramp vehicle evaluates whether the current gap is (or will be) acceptable for cooperative merging. If the mainline vehicle does not slow down, the ramp vehicle will decide whether to perform forced merge or to search for next gap. At this step, it is considered that the acceptable gap for cooperative merging is a random variable, with a mean value less than the critical gap.

Forced Merge Model

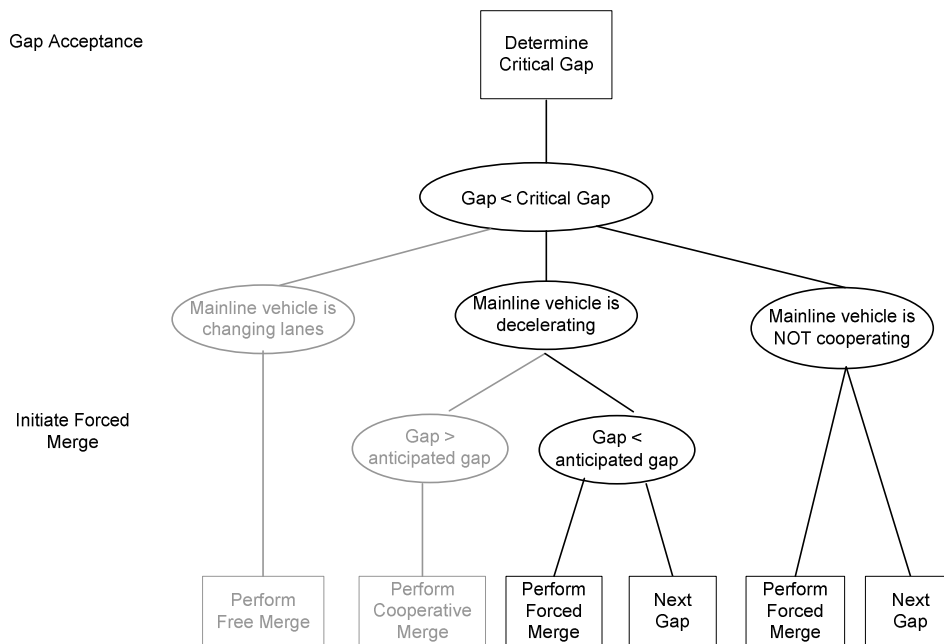


Figure 3-5. The forced-merge model.

The ramp driver will initiate a forced merge maneuver in two situations: (i) the courtesy that the mainline vehicle is providing (by slowing down) is not enough for the development of an acceptable gap for cooperative merge and the ramp vehicle decides to force its way so that the follower will decelerate more, and (ii) no action of cooperation is perceived, however, the ramp vehicle will attempt to force its way, waiting for the follower to comply. Alternatively, the ramp vehicle may decide to evaluate the next gap and return to the initial state.

Breakdown Probability Model Formulation

This section presents the structure of the breakdown probability model. As it was previously stated, the goal of this model is to bridge the gap between individual drivers' behaviors and traffic characteristics, and to provide an explanation of how the drivers' choices and actions related to merging can trigger the breakdown phenomenon at ramp junctions.

In this research it is assumed that all vehicles attempting to merge can create a certain degree of traffic instability in the freeway traffic stream. The magnitude of the turbulence depends on the maneuver type that the ramp vehicle will perform. This magnitude also depends on the degree of interaction between the ramp vehicles and the freeway through vehicles. As it was shown in the conceptual description of the merging process (Figure 3-1), there are three types of merging maneuvers: free, cooperative and forced. In terms of explaining vehicle interactions, these maneuvers can be defined as:

- Free merges: No obvious interaction exists between the merging vehicle and the mainline vehicle. The free merge maneuver does not affect the driving behavior of the mainline vehicle, and vice versa.
- Cooperative merges: The mainline vehicle yields to the ramp merging vehicle by either slowing down or changing lanes, to create an acceptable gap.
- Forced merges: There is a clear conflict between the merging vehicle and the mainline vehicle. The merging vehicle initiates this interaction and the mainline vehicle reacts by slowing down or changing lanes.

Based on these definitions of merging maneuver types, it is clear that the free merging maneuver does not create any disruption to the freeway traffic stream. However, the cooperative or forced merging maneuvers can create instabilities due to vehicle interactions which may lead to a series of vehicles slowing down to accommodate the merges and eventually, to a sprawling speed reduction (i.e., breakdown) at the location of the merge. The models developed in this thesis account for all three merging maneuver types.

Typically, the likelihood of cooperative or forced merging maneuvers increases as traffic operations move towards congested conditions, because vehicle conflicts become more frequent. Figure 3-6 shows the reaction of the mainline vehicle N, in response to the merging maneuver of the ramp vehicle R. At time $t = 0$ the mainline vehicle N at the shoulder lane identifies the intention of the ramp vehicle R to merge into the freeway. In anticipation of that fact, at time $t =$

t_1 , the mainline vehicle M may be involved in a cooperative or a forced merge maneuver with vehicle R. vehicle. The resulting action of the vehicle N would be either to decelerate, or to change lanes. It is also possible that the mainline vehicle N will not yield to the ramp vehicle R, and continue with the same speed or even accelerate to avoid any interaction.

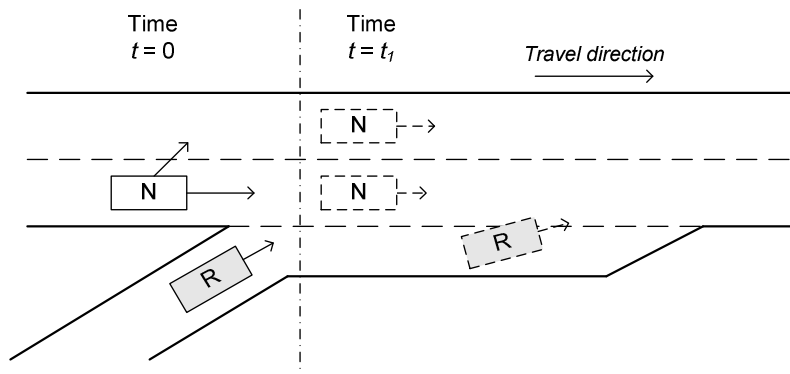


Figure 3-6. Interactions between the mainline vehicle N and the ramp merging vehicle R resulting to deceleration or lane change of vehicle N.

It is also useful to know how the behavior of the upstream vehicles is affected by the merging maneuver downstream.

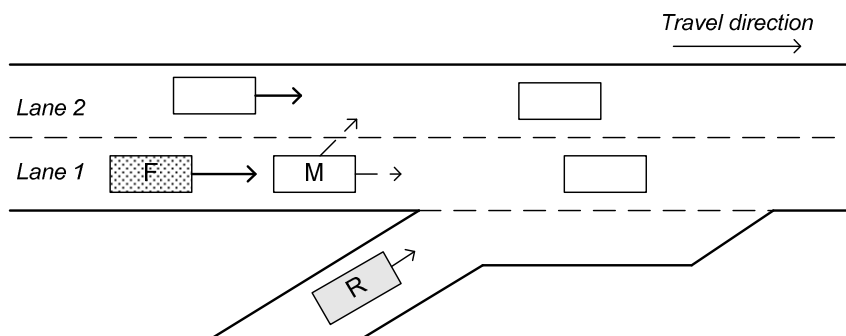


Figure 3-7. Following vehicle in shoulder lane (F) and interacting mainline (M) and ramp (R) vehicles.

For example, assume that a cooperative or a forced maneuver takes place and the mainline vehicle N decelerates to X mph (Figure 3-7). The vehicle upstream of N (vehicle F) may react to the situation ahead by decelerating as well. At this point it is clear that the merging maneuver was the cause of the speed drop for both vehicles N and F, which eventually can lead to braking

for several of the through vehicles. However, depending on spacing between vehicles F and N, it is possible that the following vehicle F does not respond at all to the situation downstream (continues with constant speed) or moves to the inside lane depending on the gap availability. Thus, vehicle decelerations as a result of the cooperative and forced merging maneuvers at a ramp junction, may affect not only the interacting vehicles but the following vehicles as well. Depending on the extent of this impact, it is possible that this interaction might trigger a chain reaction of braking and lane changing activity near the merge, which may eventually result in a breakdown.

To describe the aggregate effect of the merging vehicle's maneuvers on the traffic stream over a certain period of time, a new term is introduced, called merging turbulence: Merging turbulence is defined to occur when there is a series of cooperative or merging maneuvers, capable of affecting the speed choice of either the freeway vehicles (vehicle N or F). Thus, merging turbulence represents the frequency of ramp merging maneuvers that cause the freeway vehicles to decelerate, over a specific period of time (e.g., one minute). An illustration of turbulence is shown in Figure 3-8.

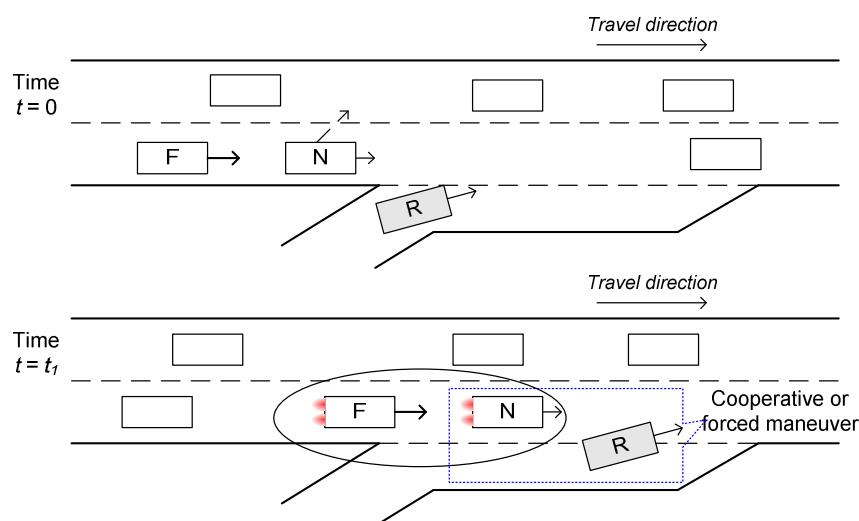


Figure 3-8. Deceleration event due to ramp merging maneuver.

At time $t = 0$, Figure 3-8 shows vehicle R entering the on-ramp. At that time, vehicles N and F are faced with three options: to continue driving with same speed, to move to the inside lane, or to decelerate. At time $t = t_1$ vehicle N decides to decelerate, and potentially forces the following vehicle F to decelerate as well. If the probability that any freeway driver N decelerates due to a cooperative or forced merging maneuver is $P_n(DEC)$, then the probability of merging turbulence can be expressed as:

$$P(MergingTurbulence) = \frac{1}{RampFlowRate} \sum_{n=1}^N P_n(Dec) \quad (3.5)$$

The following two subsections discuss the proposed models for modeling the behavior of vehicle N, to predict their contribution in the development of turbulence due to merging maneuvers, and the relationship between the merging turbulence model and the probability of breakdown.

Modeling the Behavior of the Freeway Vehicle

The probability of merging turbulence depends on the decision-making process of the freeway vehicles as they are approaching the merge area. During the ramp merging event, vehicle N has three alternatives: (i) to decelerate (and remain in the current lane), (ii) to change lanes, and (iii) to continue with the same speed in the current lane. The first two alternatives are associated with the cooperative or forced merge maneuvers. The third alternative suggests that the freeway vehicle does not yield (no cooperation is provided) or the ramp vehicle does not initiate a forced merge. In this case, the ramp vehicle will have to merge after vehicle M, and possibly interact with vehicle F. Figure 3-9 describes the potential interactions between the ramp vehicle and the freeway vehicle and the resulting decisions of the freeway vehicle. Whether the deceleration or lane changing occurs as a result of a cooperative merge or a forced merge

depends on who initiates the interaction (as described in the definitions of merging types presented in the previous section).

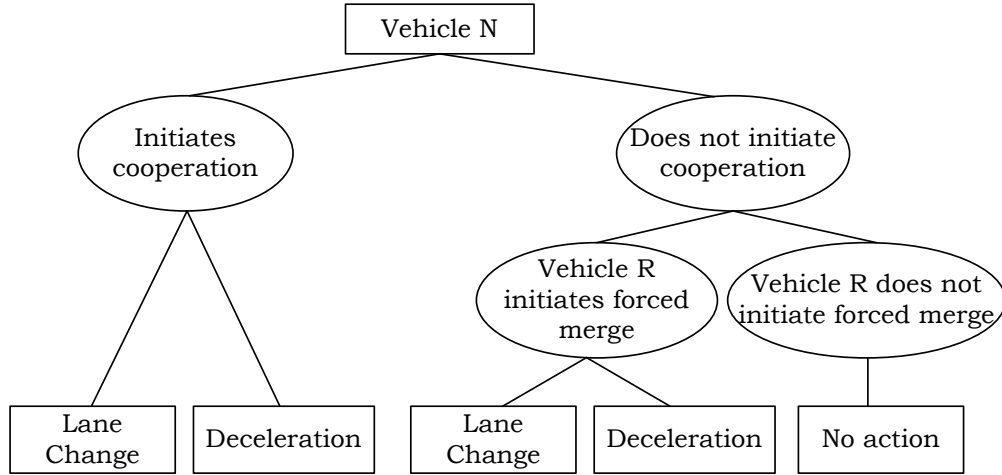


Figure 3-9. Potential freeway vehicle decisions due to a ramp merging maneuver.

As illustrated in Figure 3-9, the behavior of the freeway vehicle can be modeled considering two components. The first component describes the event that the freeway vehicle will decelerate by initiating a cooperative merge, indicating the transition from the normal state (no interaction) to the cooperative state. The second component captures the event that a freeway vehicle will decelerate as response to a forced merge by the ramp vehicle, given that no cooperation was provided earlier. This assumes the transition of the freeway vehicle from the normal state (no interaction) to the forced state. These two events are mutually exclusive, i.e., they cannot occur simultaneously. Therefore, the probability that the freeway vehicle will decelerate can be described by the following expression:

$$P_n(DEC_t) = P_n(DEC, s_{t,n} = \text{coop}/s_{t-1,n} = \text{normal}) + P_n(DEC, s_{t,n} = \text{forced}/s_{t-1,n} = \text{normal}) \quad (3.6)$$

Where s_t is the state of the freeway vehicle n at time t , which can be normal (no interaction), cooperative, or forced. Both components of this model are developed in a discrete choice framework. The exact structure of both discrete choice models is dictated by the freeway

vehicle's decision-making process. A discussion on the modeling specifications of both components follows.

Freeway vehicle behavior under cooperative merging: Assuming that the freeway driver decision-making process is a two-step process, nested structures of the model were evaluated initially. An example of a nested structure related to the cooperative merges is given in Figure 3-10.

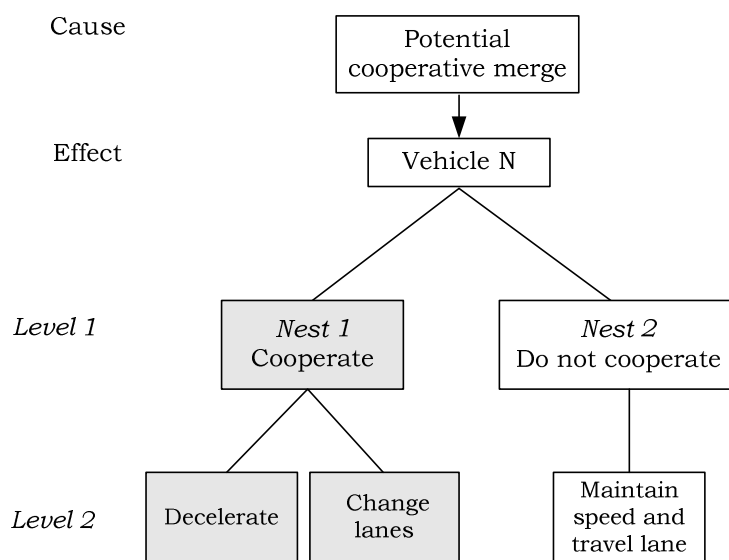


Figure 3-10. Nested model for cooperative behavior of mainline vehicle N.

According to this structure, at the first level the driver evaluates the situation and makes the decision whether to cooperate or not. If the driver is willing to cooperate, then they evaluate which form of cooperation to provide (level 2). This structure was found to be supported by the data; however, no significant explanatory variables were identified. Other nested structures were evaluated as well, but these were not supported by the data.

Therefore, the driver behavior under cooperation is modeled as a Multinomial Logit (MNL) model where the freeway vehicle has three choices: to decelerate, to change lanes, to do

nothing. If gaps are not available, then lane changing is not an option, thus the freeway vehicles' choices are to decelerate or not yield to the ramp vehicle.

Freeway vehicle behavior under forced merging: If the freeway vehicle does not show cooperation towards the ramp vehicle, then the ramp vehicle may attempt to force its way into the freeway (Figure 3-9). In this case, the role of the freeway vehicle is reactive. They can either decelerate or move to the inside lane, provided that there is a gap available. The freeway vehicle's decision is also modeled as a Multinomial Logit (MNL) model.

For the development of both behavioral models under cooperative, forced or normal state, the utility functions (U) of the choices for the freeway vehicle N have the property that an alternative is chosen if its utility is greater than the utility of all other alternatives in the individual's choice set. These functions are:

$$U_{i,n}^s = V_{i,n}^s + \varepsilon_{i,n}^s \quad (3.7)$$

$$i \in \{decelerate, change\ lanes, no\ action\}$$

$$s \in \{cooperative, forced, normal\}$$

In Equation 3.7 $V_{i,n}^s$ represent the observable (deterministic) portion of the utilities of driver n to decelerate, change lanes and do nothing under either state. The terms $\varepsilon_{i,n}^s$ are the error terms associated with the three utilities. The error terms are assumed to be Gumbel distributed and also identically and independently distributed across the alternatives and across the individuals.

The deterministic components of the utilities for all three choices are:

$$V_{CL,n}^s = X_{CL,n}^s \cdot \beta_{CL,n}^s \quad (3.8)$$

$$V_{NoAction,n}^s = X_{NoAction,n}^s \cdot \beta_{NoAction,n}^s \quad (3.9)$$

$$V_{DEC,n}^s = X_{DEC,n}^s \cdot \beta_{DEC,n}^s \quad (3.10)$$

Where $X_{CL,n}^s$, $X_{DEC,n}^s$ and $X_{NoAction,n}^s$ are the vectors of explanatory variables that affect the utilities to change lane, decelerate and do nothing. $\beta_{CL,n}^s$, $\beta_{DEC,n}^s$ and $\beta_{NoAction,n}^s$ are the corresponding vectors of the parameters.

Generally, the explanatory variables are related to: (1) alternative-specific attributes, (2) characteristics of the drivers, and (3) interactions between the attributes of the alternatives and the characteristics of the drivers. The function that describes the decision of vehicle N to decelerate, change lanes or do nothing has the following form:

$$V_n^s = \alpha_0 + \beta * X_n + \gamma * Z_n + \delta * (X_n Z_n) \quad (3.11)$$

$s \in \{cooperative, forced, normal\}$

In Equation 3.11, α_0 are the alternative-specific constant parameters, X_n is the vector of explanatory variables related to the traffic conditions and the environment of the subject vehicle, β are the parameters associated with explanatory variables X_n , Z_n is the vector of variables related to the characteristics of the driver, γ are parameters associated with explanatory variables Z , δ are parameters associated with the interaction terms between the explanatory variables, X , and driver characteristics variables, Z .

The final expressions for the probabilities of all three alternatives are:

$$P_n(DEC, s_t = j / s_{t-1} = normal) = \frac{\exp(V_{DEC,n}^j)}{\exp(V_{DEC,n}^j) + \exp(V_{CL,n}^j) + \exp(V_{No-Action,n}^j)} \quad (3.12)$$

$$P_n(CL, s_t = j / s_{t-1} = normal) = \frac{\exp(V_{CL,n}^j)}{\exp(V_{DEC,n}^j) + \exp(V_{CL,n}^j) + \exp(V_{No-Action,n}^j)} \quad (3.13)$$

$$P_n(No - Action, s_t = j / s_{t-1} = normal) = \frac{\exp(V_{No-Action,n}^j)}{\exp(V_{DEC,n}^j) + \exp(V_{CL,n}^j) + \exp(V_{No-Action,n}^j)} \quad (3.14)$$

Merging Turbulence and the Probability of Breakdown

The merging turbulence model accounts for the effect of the merging maneuvers on the occurrence of the freeway flow breakdown. The merging turbulence model should be compared with a breakdown probability model to evaluate their relationship.

To account for the stochastic nature of the breakdown, the method for developing the breakdown probability model is based on the lifetime data analysis, and particularly the Kaplan-Meier estimation method, as this was introduced by Brilon (2005). For the development of this model, historic speed-flow data at the breakdown location are required. The distribution function of the breakdown volume $F(q)$ is:

$$F(q) = 1 - \prod_{i: q_i \leq q} \frac{k_i - 1}{k_i}; i \in \{B\} \quad (3.15)$$

In Equation 3.15 q is the total freeway volume (veh/h), q_i is the total freeway volume (veh/h) during the breakdown interval i , (i.e., breakdown flow), k_i is the number of intervals with a total freeway volume of $q \geq q_i$ and $\{B\}$ is the set of breakdown intervals (1-minute observations).

The breakdown interval is typically identified as the interval when the average speed at that location drops below a specific threshold (e.g., 10 mi/h lower than the posted speed limit).

Methodological Framework

This section presents the data that are required for the development of the driver-behavior models and the macroscopic models of merging turbulence and breakdown probability, as these were described in the previous sections of this chapter. The chapter concludes with a step-by-step summary of the methodology pertained in this thesis.

Data Types for Models

The development of the microscopic driver behavior models require data related to the drivers' thinking process, the interactions with the adjacent vehicles and the traffic conditions on the freeway.

The drivers' thinking process is required to investigate when they start (or fail) to interact and cooperate with their adjacent drivers, what actions they are performing to accomplish their decision (decelerate, change lanes or do nothing), how they perceive the adjacent vehicles and if they see any cooperation (or not) from the adjacent vehicles. In additions, drivers' characteristics are also important to examine how their decisions vary across traffic conditions and across different drivers. To obtain driver behavior-related information, actual input from different drivers is required. This could be through conversations with drivers in the format of focus group sessions, as well as actual driving observations, where driver actions and reactions are observed from the inside.

Data that describe the relationship between the subject vehicle and the adjacent vehicles in the traffic stream are also required to produce the variables used in the models. This type of data include the gaps and gap change rates between the ramp vehicle and the freeway lead/lag, their relative speeds and accelerations, the positions of the freeway lag when the ramp vehicle enters the acceleration lane, the percent of acceleration lane used, the position of the freeway lag and lead vehicles during the merging maneuver. Other types of information, such as the type of the interacting vehicles are also required. These data can easily be obtained through video observations, however this should be at the individual vehicles level. Video observations taken from inside the vehicle can provide the quantitative data that are related to drivers' actions and triggers.

Data related to the prevailing traffic conditions are required to quantify their effect on the choices of the interacting vehicles. These data include measurements of densities and average speeds during the merging maneuver, as well as the availability of gaps in the adjacent lanes. The number of ramp vehicles at the time of the merge is also considered as this may affect both the decisions of the freeway lag and the ramp vehicle. Data taken from cameras (e.g., traffic monitoring cameras) that cover the entire merge areas are required to obtain the macroscopic information.

For the development of the turbulence model video data at the merge junction before the occurrence of the breakdown are required to distinguish between the different sources of vehicle interactions (due to merging, lane changing or due to speed reduction downstream), and to quantify the effect of those interactions to the freeway vehicles. These effects include decelerating or lane changing activity for each lane. In addition, information about the ramp volume and the freeway volume are required to provide correlation between the turbulence model and the breakdown occurrence. To verify the breakdown occurrence speed time-series plots need to be constructed from the detector sensors close to the merge area. Historic detector data for the breakdown locations are also required to construct the breakdown probability model as this was described in the previous section.

In summary, various sources of data are required to observed driver behavior and its relation to the development of the breakdown. Focus group discussions, as well as simultaneous data collection using an instrumented vehicle and traffic monitoring cameras are appropriate sources for identifying how merging decisions affect traffic operations and the breakdown occurrences on freeway merges.

Research Tasks

The step-by step procedure performed in this thesis is summarized in this section. An illustration of the entailed tasks is shown in Figure 3-11.

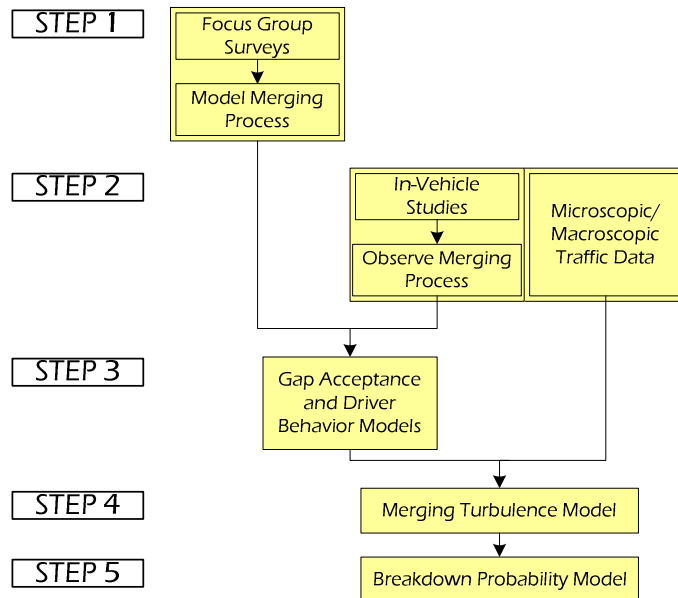


Figure 3-11. Methodological plan.

Step 1 - Conduct focus group meetings: In the first step, focus group surveys were conducted to attain knowledge about how drivers perform merging maneuvers and what are their concerns. During this step, all important factors indicated from the drivers were used to finalize the merging process and to formulate the merging models that are calibrated as part of Step 3. A detailed description of this data collection effort and results is provided in Chapter 4 of this thesis, while the questionnaires used during the focus group discussions is provided in Appendix A.

Step 2 - Conduct field data collection effort: In this step, drivers were asked to participate in in-vehicle driver behavior studies. Typically, drivers' intention and process of thinking related to the merging task cannot be captured by observing field operations, because only the result of their actions is captured this way. Drivers' thinking process can only be

obtained through questionnaires, where they can explicitly describe their intention about a maneuver.

These studies aim at obtaining such driver behavior data from participants during their driving task (merging on the freeway and driving on the mainline). Additional field data (flow, speed, density) were collected concurrently with the in-vehicle data at the study ramp merging sections. The combination of in-vehicle and traffic data is used to infer vehicle interactions in two ways: how the driver merging decisions influence and are influenced by the prevailing traffic conditions. The field data collection was performed at near-to-congestion conditions to capture the impact of these interactions on the freeway operations. Information relevant to the in-vehicle and field data collection and results is presented in detail in Chapter 5.

Step 3 - Calibrate the merging models: This step includes the calibration of the gap acceptance and the driver behavior models. All data collected in the field, from both the in-vehicle study and the external traffic data were used for the model calibration. The gap acceptance model considers the different types of merging maneuvers and evaluates the impact of driver behavior attributes on those maneuvers. The driver behavior models capture freeway drivers' decisions to decelerate, change lanes or not interact with the ramp merging traffic.

Step 4 - Develop merging turbulence models: During this step, the contribution of individual drivers' action on the freeway traffic stability is evaluated. The external traffic data were used to quantify the effect of individual vehicle deceleration decisions and associate those with the beginning of congestion.

Step 5 - Develop breakdown probability model: This step includes the proposed application of the turbulence model to develop a breakdown probability model.

CHAPTER 4 FOCUS GROUP EXPERIMENTS

The first part of the data collection plan undertaken for this research is presented in this chapter. The focus of this research is to look at merging behavior and vehicle interactions from the drivers' perspective, and to investigate the effect of individual behavioral characteristics on drivers' decisions. Focus groups were used as a first step to understand the drivers' thinking process when merging. The forms as well as the methodology used for the focus group meetings were pre-approved by the Institutional Review Board (IRB) of the University of Florida.

This chapter describes the formulation of the focus groups and presents the questions discussed during these sessions. Important focus group findings and conclusions from the discussions are also presented.

Setting Up the Focus Groups

The focus group study was advertized through local organizations in Gainesville, FL, and candidates completed a pre-screening questionnaire. The pre-screening questionnaires assembled information on gender, age-group, ethnicity, years of driving experience, occupation, frequency of driving and time of day, and vehicle type. The information was used to select a diverse set of participants for focus group participation. Seventeen participants were invited to join three 2-hour focus groups, and an attempt was made to select drivers with different demographics, in terms of their gender, age-group and race. The demographics of all participants are presented in Table 4-1.

Table 4-1. Demographic characteristics of focus group participants

ID	Gender	Age group	Race	Experience	Occupation	Driving frequency	Hours per week	Peak/non-peak	Vehicle ownership
Focus Group 1									
1_03	Female	25-35	Caucasian	>=10 years	Teacher	Everyday	>14 hrs	Peak	Sedan/Coupe
1_05	Male	25-35	Caucasian	>=10 years	Teacher	Usually	<4hrs	Peak	Pickup/SUV
1_09	Male	45-55	Caucasian	>=10 years	Community design	Sometimes	4-8 hrs	Non-peak	Sedan/Coupe
1_22	Male	25-35	Caucasian	>=10 years	Student	Everyday	4-8 hrs	Peak	Sedan/Coupe
1_01	Female	25-35	Caucasian	>=10 years	Student	Everyday	4-8 hrs	Peak	Sedan/Coupe
1_15	Female	25-35	Caucasian	>=10 years	Legal assistant	Everyday	4-8 hrs	Peak	Sedan/Coupe
Focus Group 2									
2_13	Female	55-65	Caucasian	>=10 years	Accountant	Everyday	8-14 hrs	BOTH	Sedan/Coupe
2_12	Female	35-45	Caucasian	>=10 years	Massage therapist	Everyday	8-14 hrs	Peak	Pickup/SUV
2_16	Female	18-25	Afr/American	3-9 years	Student	Sometimes	>14 hrs	Non-peak	Sedan/Coupe
2_07	Male	18-25	Caucasian	3-9 years	Attorney	Everyday	4-8 hrs	Peak	Sedan/Coupe
2_25	Female	35-45	Caucasian	>=10 years	Student	Everyday	8-14 hrs	Peak	Sedan/Coupe
Focus Group 3									
3_26	Male	35-45	Caucasian	>=10 years	US Navy	Everyday	4-8 hrs	Peak	pickup/SUV
3_04	Male	18-25	Caucasian	3-9 years	Student	Everyday	>14 hrs	Peak	Sedan/Coupe
3_06	Male	18-25	Afr/American	3-9 years	Student	Sometimes	4-8 hrs	Peak	Sedan/Coupe
3_14	Male	35-45	Caucasian	>=10 years	Manager	Everyday	4-8 hrs	BOTH	Sedan/Coupe Truck
3_27	Female	55-65	Caucasian	>10 yrs	Retired economist	Usually	4-8 hrs	Non-peak	Sedan/Coupe
3_28	Female	25-35	Hispanic	>10 yrs	Real-estate	Everyday	4-8 hrs	Peak	Sedan/Coupe

Prior to each session, the participants completed a background survey form, which contained seven multiple-choice questions related to their driving habits. These questions solicited the subjects' desired freeway speed (assuming good visibility and weather conditions and a 70-mi/h speed limit), lane-changing habits, how aggressive they consider themselves, how aggressive their friends/family consider them, when and where they typically merge onto the freeway, how they react if a vehicle merges onto the freeway while they are driving on the right-most lane, and whether they plan their trips allowing for additional time to mitigate possible delays.

Overview of Focus Group Questions

Typically, focus group discussions contain five categories of questions, all of which have their specific purpose and function (Krueger and Cassey, 2000): opening, introductory, transition, key, and ending. The opening question is designed to get people talking and make them feel comfortable. They were asked if they enjoy driving and if they spend a lot of time driving. The next question is the introductory question which helps people relate to the topic. Here, the participants were asked "What is the first thing that comes to mind when you hear the phrase 'Merge into the freeway'?" The transition question moves the conversation to the key questions. The transition question used was phrased as follows: "Do you believe the way you merge is different from other drivers? Why or why not?". The key questions are the ones that typically drive the study. The key questions are open-ended situation-based scenarios, and the central idea is to obtain the thinking process and potential actions in a merging maneuver. These scenarios are discussed in detail in the following section. The ending question ensures that all important topics have been covered. A handout containing all key questions and ending question was given to the participants to fill out throughout the session.

Focus Group Key Questions

The goal of the key questions is to obtain the participants' thinking process and potential actions in various scenarios, either as the merging vehicle or the freeway vehicle. Scenarios under different amounts of congestion were discussed. The effect of other factors (e.g., ramp geometry, vehicle type, driver's urgency) on driver behavior was also discussed. Participants were asked to report (up to five) factors that affect their decisions and assign an importance level ("very important", "somewhat important", and "not as important but may consider") to each factor. These three levels were transcribed into the following importance values for analysis purposes: "very important" value = 3, "somewhat important" value = 2, and "not as important" value = 1. The following five scenarios were discussed

Question 1 – Merging Process Under Free-Flowing Conditions and Selection of Acceptable Gaps

Participants were shown Figure 4-1A and B and were asked to provide their actions and thinking process assuming they are the merging vehicle just entering an on-ramp, while the freeway vehicles are traveling at their desired speeds. Both cases of parallel and taper ramps were discussed.

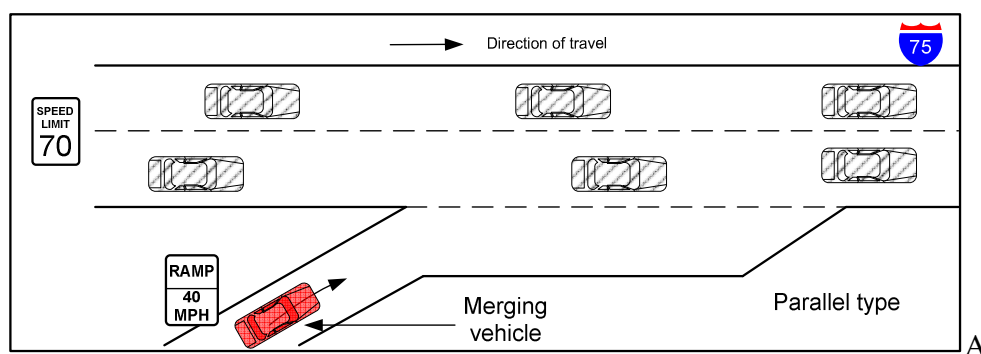


Figure 4-1. Figures discussed during scenario 1 A) Merging process under parallel type on-ramp. B) Merging process under tapered type on-ramp. C) Lagged position of merging vehicle with respect to freeway vehicle. D) Parallel position of merging vehicle with respect to freeway vehicle.

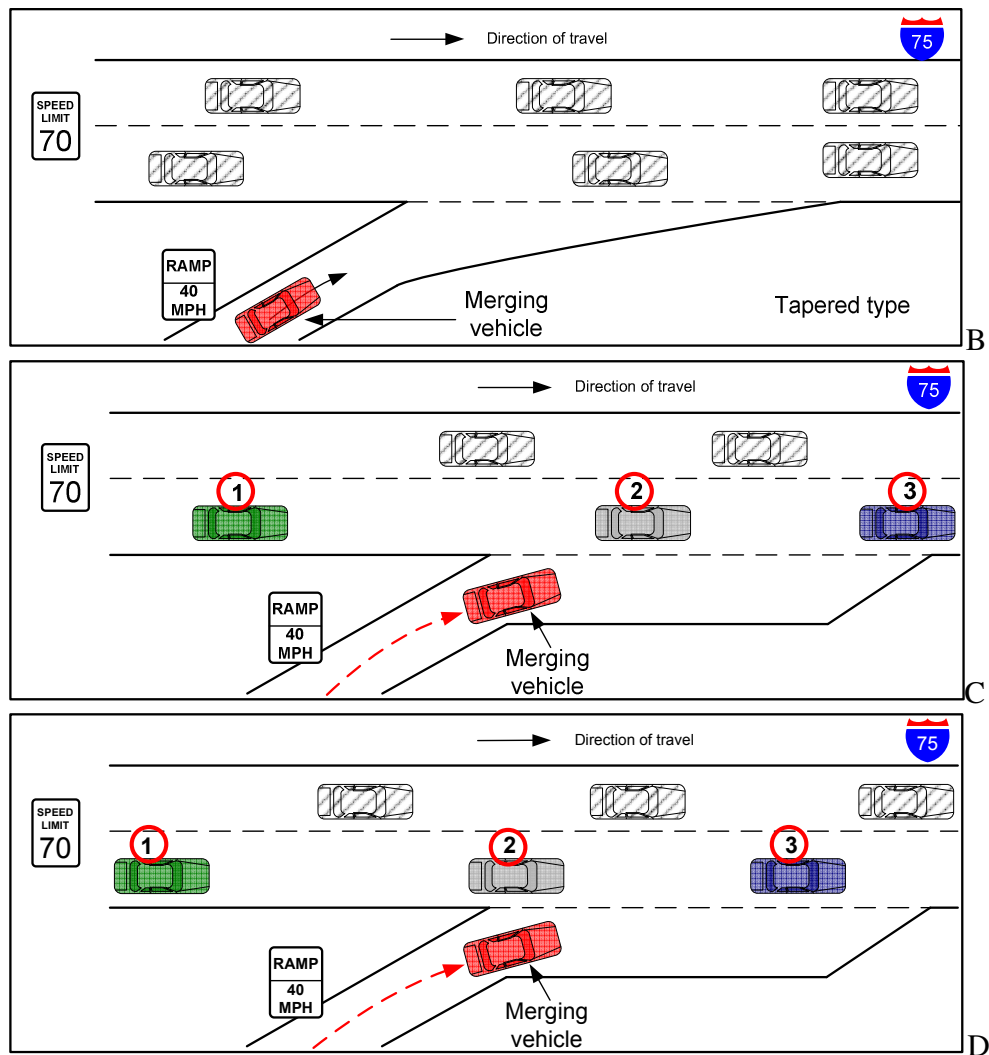


Figure 4-1. Continued.

Participants were asked to list and discuss their actions and thought process when merging into the freeway, given the presence of freeway vehicles (vehicles 1, 2, and 3) at the locations shown in Figure 4-1C and D. The participants discussed their preferable gaps in each case, as well as the factors affecting their preference. The effect of vehicles 1, 2, or 3 being trucks in the gap decision was also discussed.

Question 2 - Merging Process Under Decreased Speed (40-60 mi/h)

For this question the participants were asked first to assume that they are the merging vehicle reaching the acceleration lane, where traffic is denser and vehicles' speeds are low (40-60 mi/h). They were also asked to report their thinking process in merging under those conditions, and how this would change if there was another vehicle present on the acceleration lane (moving towards the end of the lane). Then, they would list their actions assuming they are the freeway vehicle on the right lane reaching the merging section and observing at least one vehicle on the ramp trying to merge.

Question 3 - Cooperative Merging and Forced Merging Maneuvers Under Decreased Speed (40-60 mi/h)

This question investigated the likelihood of initiating a cooperative merge (as the freeway vehicle), and a forced merge (as the merging vehicle), as well as factors (up to five) that affect each decision. In both cases participants had to select between the "very likely", "somewhat likely", and "not so likely" responses. Participants were asked to rank their stated factors as "very important", "somewhat important", and "not as important but may consider". The definitions of cooperative and forced merges used in this question derive from the literature (Hidas, 2005), but modified to consider specifically the freeway vehicle actions after the merge:

- Cooperative merge: the gap between the freeway leader and follower is increasing before the merge, indicating that the follower decelerates or changes lanes to allow the ramp vehicle to enter.
- Forced merge: the gap between the leader and follower is either constant or narrowing (follower maintains speed or accelerates) before the initiation of the merge, and starts to increase as the ramp vehicle enters, indicating that the ramp vehicle has "forced" the follower to either decelerate or change lanes.

Question 4 - Merging Under Stop-and-Go Traffic

Participants were asked to assume that the freeway is congested (stop-and-go traffic). The discussion concerned participants' actions when starting a forced merge (as the ramp vehicle),

and when giving way to a ramp vehicle that initiated a forced merge (as the freeway follower).

They were also requested to express the likelihood of performing these maneuvers (“very likely”, “somewhat likely”, and “not so likely”).

Question 5 - Effect of other people on driving behavior

This last question obtained information related to the effect of other people’s presence in the vehicle, in driving performance.

Assembly of Focus Group Data

The data from the focus groups contained: (i) voice recordings of the 2-hour sessions, (ii) documentation of the participants’ background survey form, and (iii) documentation of participants’ responses on distributed handouts during the session. Before analyzing the data, the voice recordings for each focus group were transcribed, and matched with the responses obtained from the handouts.

Overview of the Freeway-Ramp Merging Process

This section presents the focus group findings related to participants stated actions and thinking process while merging.

Refining Merging Process Under Free-Flowing and Dense Traffic

Based on participants’ responses, a series of steps was developed for merging under both free-flowing and dense traffic conditions. The process was found to be similar for all participants. These steps are summarized below:

- Step 1: As drivers arrive on the on-ramp, most of them first think about merging when they have a clear view of the freeway traffic (this depends on the ramp design). Others when they are half way on the on-ramp, or when they have accelerated to a speed of 50-55 mi/h.
- Step 2: Most of the drivers become aware of their surroundings. They check: (i) their side to assess the speed and flow of traffic on the right lane (possibly the left lanes too), (ii) their front to evaluate the length of the acceleration lane and the time left for merging, and (iii) their rear to acknowledge potential followers.

- Step 3– free-flowing conditions: All drivers start to accelerate when arriving at the beginning of the acceleration lane. The acceleration and speed adjustment may be related to targeting a specific gap that was visible from the on-ramp, which could be used for merging. If there is no vehicle in front, all drivers want to reach a speed close to the freeway speed or the speed limit, as the optimal speed for merging. Some drivers indicate they target a specific gap at this stage.
- Step 3– dense conditions: Several drivers indicated they would accelerate as soon as entering the acceleration lane to match or even drive 5 mi/h faster than the freeway traffic. Due to the denser traffic (speeds are lower), there is less variability in speeds, therefore the vehicle can adjust its speed immediately, and there is no need for fast acceleration.
- Step 4 – free-flowing conditions: This step includes the gap acceptance and merging process. If a gap has not been targeted through the acceleration process, the drivers select a gap and may adjust their speed to fit the gap. Tasks such as actuating the turn signal and checking of the mirrors or blind spots follow. Most of the participants (16 out of 17) indicated they would accept a minimum gap of 2 – 3 vehicle lengths, while only one participant indicated they would accept a gap of about 5 vehicle lengths.
- Step 4 – dense conditions: The gap acceptance and merging process is similar. Additional considerations: if the acceleration lane is long enough, they might consider going faster than the rest of traffic and decelerate if necessary, to allow more opportunities to get in (one participant). On the other hand, another participant stated that if speed was low (about 40 mi/h) she might consider letting 1-2 vehicles pass before merging, to assess the traffic conditions downstream (e.g., presence of stopped vehicles). All participants agreed that the acceptable gap size in this case ranges from 1.5 to 2 car lengths.
- Step 5: After merging, several drivers may consider moving to the inside lane, especially if the right-most lane is slow.

Focus Group Results for Gap-Acceptance

When participants were asked to compare their merging process (Figure 4-1A and B), several suggested that, in taper ramps they would be more cautious and anxious to merge. Fourteen also indicated they would accelerate sooner and faster than in the parallel type on-ramp, and that they would be more aggressive in selecting a gap. However, two participants suggested being less aggressive, and less worried about their acceleration, but more worried about finding a gap to merge with lower speed. Both these participants drive manual cars, and indicated so independently, as they were in different focus groups.

When participants were asked to select a preferred gap (Figure 4-1C and D) their answer differed as a function of several parameters. In Figure 4-1C, almost all participants (16 out of 17) chose the gap between vehicles 1 and 2, while one chose the gap after vehicle 1. Participants' decision to choose the gap between vehicles 1 and 2 depends on:

- Speed of vehicle 1
- Speed/deceleration of vehicle 2
- Presence of vehicles behind vehicle 1
- Whether vehicle 1 changes lanes

Six participants that initially chose the gap between vehicles 1-2 might consider merging in front of vehicle 2. This depends on:

- Speed of vehicle 1
- Speed/deceleration of vehicle 2
- Change rate of gap between 1 and 2
- Whether vehicle 2 is a truck

Alternatively, the decision (of 12 participants) to merge after vehicle 1 depends on:

- Speed of vehicle 1
- Whether vehicle 1 is a truck
- Presence of vehicles behind vehicle 1
- Whether vehicle 2 is a truck
- Relative speed between merging vehicle and vehicle 2
- Acceleration capabilities of merging vehicle
- Freeway speed

Almost all participants (16 out of 17) would merge between vehicles 1 and 2 or after 1, while only a few (6 out of 17) would merge between 2 and 3. This selection changes if the merging vehicle is approximately at the same lateral position with vehicle 2 (Figure 4-1D). In this case, drivers would prefer to merge between vehicles 2 and 3 (12 out of 17), depending on:

- Relative speed between merging vehicle and vehicle 2
- Speed/deceleration of vehicle 2
- Acceleration capabilities of the merging vehicle
- Change rate of gap between 2 and 3
- Whether vehicle 2 is a truck

Comparison of the two figures showed that the majority of the participants (14 out of 17) would merge between vehicles 1-2 or 2-3 (Figure 4-1D) given that previously they selected gaps after 1

and 1-2, respectively (Figure 4-1C). The remaining three would select the same gaps in both cases.

In summary, it was observed that under the same situation, drivers would likely react differently, and that each driver considers different factors for making their decision. Some drivers are more likely to choose a specific gap, while others may choose any of the three gaps, depending on the traffic conditions.

Focus Group Results for Cooperative and Forced Merging

A significant portion of the focus group discussion aimed in understanding the drivers' thought process while being either on the freeway approaching a merging section, or the on-ramp. The purpose of this discussion was to identify factors that affect:

- Cooperation of the freeway vehicle towards the ramp vehicle by decelerating or changing lanes.
- Whether the ramp vehicle forces its way onto the freeway.
- Whether the freeway vehicle yields to a ramp vehicle by decelerating or changing lanes when the later initiates a forced merge.

Throughout the discussion, several factors that affect drivers' decisions were identified and grouped into the following categories:

- Environmental Factors: These include the roadway, weather and lighting conditions.
- Freeway Vehicle Factors: These are associated only with the freeway vehicle/driver.
- Ramp Vehicle Factors: These are associated only with the ramp vehicle/driver.
- Interaction Factors: These pertain to the relation between the subject vehicle and another vehicle of the immediate environment (e.g., relative speed).
- Traffic Factors: These are associated with the general traffic conditions of the merging segment (e.g., average speeds, gap availability).

Table 4-2 presents all factors reported to affect vehicle decisions to cooperate towards a merging maneuver, their frequency, and average importance. The average importance is a

measure of both frequency and importance value and it is calculated as the frequency-weighted average of importance.

Table 4-2. Factors affecting cooperative merge decisions for freeway vehicles

Factors for cooperative merging	Frequency	Avg. importance (max=3)
Weather	2	2.5
Lighting conditions	1	2.0
Speed of vehicle 1	3	3.0
Emotional status	1	3.0
Route selection	1	3.0
Headway between vehicle 1 and upstream vehicle	5	2.2
Speed of upstream vehicle	2	2.5
Vehicle 1 - ramp vehicle relative speed	1	3.0
Speed of vehicle 2	1	2.0
<i>Speed/acceleration capabilities</i>	9	2.7
<i>Vehicle size/type</i>	6	2.5
Distance traveled/position on acceleration lane	4	2.8
Competency - Erratic behavior	2	2.5
Traffic awareness (eye-contact)	2	2.5
Previous unsuccessful merges	1	3.0
Attempt to start a forced merge	1	3.0
<i>Gap availability on left lane</i>	8	2.8
Speed in all/left lanes	5	2.8
Traffic congestion	2	2.0
Coop. behavior of other freeway vehicles	1	3.0
Lane-changing activity	1	2.0

In the cooperative merge case, the participants are assumed to be the freeway vehicle (vehicle 1, Figure 4-1C). The three most important factors highlighted in this table are:

- Speed/acceleration capabilities of the ramp vehicle: If the participants perceive that the ramp vehicle has achieved a reasonable merging speed, they are willing to yield. This perception depends on the make/type of the vehicle, but also the driver (primarily age).
- Gap availability on left lane: Participants are very likely to give way to the ramp vehicle, if they can move to the inside lane. This is consistent with the responses to Question 2, which investigated participants' actions when approaching the merge area from the freeway (right lane).
- Size/type of the merging vehicle: Participants that consider this factor are reluctant to cooperate with trucks, especially if these are open-bedded or if they are stopped at the end of the acceleration lane. One participant indicated willingness to decelerate for a motorcycle.

Table 4-3 presents the stated factors that affect drivers' decisions to initiate a forced merge maneuver. In the forced merge case, the participants are assumed to be the ramp vehicle. The three most important factors highlighted in Table 4-3 are:

- Average speed on the freeway: ramp vehicles are more likely to force their way in if freeway speeds are low and traffic is dense.
- Amount of congestion and gap availability on the right lane: These two factors are grouped together because they are correlated. The more congested the freeway, the less available gaps exist, and drivers are more willing to perform a forced merge.

Table 4-3. Factors affecting forced merge decisions for ramp merging vehicles

Factors for forced merging	Frequency	Avg. importance (max=3)
Roadway conditions	3	2.3
Weather	2	3.0
Speed of vehicle 2	3	2.7
Vehicle size-type	5	3.0
Relative speed between vehicle 2 and ramp vehicle	2	3.0
Coop. behavior of vehicle 2	1	2.0
Speed/acceleration	6	2.7
Emotional status	1	3.0
Position on acceleration lane	1	3.0
<i>Speed in all/right lanes</i>	9	2.6
<i>Gap availability on right lane</i>	7	3.0
<i>Traffic congestion</i>	7	2.9
Number of following vehicles on ramp	2	2.0
Number of leading vehicles on ramp	1	3.0
Gap availability farther upstream	1	2.0

Table 4-4 presents the factors that affect drivers' decisions to yield to a ramp vehicle that forces its way in, by either decelerating or changing lanes. Participants were asked to assume they are freeway vehicle 1 of Figure 4-1C. Table 4-4 includes all factors reported by the participants. The three most important factors for the decision to decelerate or change lanes are shown in italics.

Table 4-4. Factors affecting deceleration and lane-changing decisions of freeway vehicle, when a ramp vehicle has initiated a forced merge

Factors for deceleration	Frequency	Avg. importance (max=3)
Roadway conditions	1	3.0
Weather	1	2.0
Headway between vehicles 1 and 2	5	2.8
Speed of vehicle 1	4	2.8
Relative speed between vehicle 2 and ramp vehicle	1	3.0
Headway between vehicles 2 and 3	1	2.0
<i>Speed/ acceleration/ deceleration capabilities</i>	5	3.0
Vehicle size/type	3	2.3
Position on acceleration lane	1	3.0
<i>Gap availability on left lane</i>	12	2.9
<i>Speed/relative speed in all/left lanes</i>	8	2.4
Traffic congestion	2	2.5
Factors for lane-changing	Frequency	Avg. importance (max=3)
Roadway conditions	1	3.0
Speed	2	3.0
Route selection	2	2.5
Trip urgency	1	2.0
Headway between vehicles 1 and 2	5	2.8
Relative speed between vehicle 2 and ramp vehicle	1	3.0
<i>Speed/acceleration</i>	8	2.9
Vehicle size/type	2	2.0
<i>Gap availability on left lane</i>	12	2.9
<i>Speed/relative speed in all/left lanes</i>	9	2.3
Traffic congestion	4	3.0

The most important factors shown in Table 4-4 are:

- Gap availability in the left lane: If there are gaps in the inside lane they will change lanes, otherwise they will decelerate.
- Freeway speed (or relative speed between lanes): If the speed of the left lane is less than the speed of the right-most lane, then there is not much incentive for the freeway vehicle to change lanes, thus, it will remain to the right lane and decelerate. However, if the speed in the inside lanes is higher, they would be more willing to change lanes. This factor is related to the amount of deceleration that the freeway vehicle is willing to accept. The

freeway vehicle is not willing to decelerate significantly, thus, if the merging vehicle forces them to, they will likely move to the left lane.

- Speed/acceleration capabilities of the ramp vehicle: Similar to the cooperative merge, the freeway vehicle is more likely to change lanes if it perceives that the ramp vehicle cannot accelerate to the merging speed, or will not match the freeway speed quickly once it has merged onto the freeway.

Relationships Between Driver Behavior and Driver Characteristics

Driver behavior is related to the individual's characteristics, vehicle capabilities, the traffic/geometric environment, and also the task performed. This section identifies differences in driver behavior, categorizes the stated behaviors as aggressive, average and conservative, and evaluates whether drivers are consistent in degree of aggressiveness under various scenarios. Based on focus group analysis aggressive behavior can be described by "selfishness" and consideration of factors that affect mostly the subject vehicle. An average behavior can be defined as considering both the subject vehicle status and the other vehicles. A conservative behavior is assumed to occur when the subject vehicle will only act as a response to the other vehicles' actions. For the purposes of evaluating driving behaviors vs. driver characteristics, the focus group scenarios of cooperative and forced merging maneuvers under both dense and stop-and-go traffic conditions were considered.

An attempt was made to categorize different behaviors in the case where the participants are on the ramp, under dense traffic conditions. Participants were asked to discuss how likely they are to initiate a forced merge. These responses, along with the discussion on how competitive and considerate of other vehicles they are, were grouped. The following categories are distinguished:

- Aggressive behavior: participants would not hesitate to cut somebody off if they only had one chance. They have a sense of pressure and eagerness to get in, and not run out of space. They assume that others will let them in. These participants consider mostly factors associated with their own individual status when making the decision to merge.

- Average behavior: participants will consider a forced merge, but their decision also depends on the prevailing traffic (available gaps, speeds) and their perception of the freeway vehicles. Their decision to merge depends equally on their own status and the surrounding traffic conditions.
- Conservative behavior: they are less likely or not likely at all to attempt a forced merge under any situation. These participants will probably wait for a large gap to merge without causing any disruption on freeway vehicles.

Participants' responses were also grouped for the scenario of the cooperative merge under dense traffic conditions. Even though both options of deceleration and lane-changing were given, all of the participants responded that lane-changing is their first choice. In fact, some participants reported they would be moving to the inside lane "out of habit". Thus, the distinction of the different behaviors was based on the event that lane-changing is not a feasible option (no available gaps on the left lane). Given that, behavior was categorized as follows:

- Aggressive behavior: participants are not very likely to start a cooperative merge by decelerating. They will at least maintain their speed so the ramp vehicle merges behind them. Also, they are not likely to initiate a cooperative merge if the ramp vehicle is stopped at the acceleration lane. They might decelerate only if the merging vehicle is approaching the end of the lane but still moving, and traffic permits.
- Average behavior: these drivers are willing to decelerate and create gaps for the ramp vehicle to merge; however, they are not willing to decelerate significantly. These drivers appear to be more cautious about stopped vehicles at the end of the ramp, because they believe these could make poor judgments at merging.
- Conservative behavior: these drivers will firstly consider decelerating, than changing lanes. This behavior was not represented in the focus group.

Similar analysis was performed for the remaining scenarios that deal with congested conditions. The first case deals with ramp vehicles' willingness to wait on the on-ramp for a larger gap instead of forcing their way in. Driver behavior was categorized as follows:

- Aggressive behavior: Participants feel that forcing their way in is their only option, thus there is a high probability that they will force their way into the freeway. They also feel that the freeway vehicles are more willing to give way, because everybody is in the same position, sharing the same motivation. They will mostly consider themselves when making the decision to merge.

- Average behavior: Participants prefer making eye-contact with the freeway vehicle and wait for them to signal, or a gap to form. Their thinking process involves the surrounding freeway vehicles as well. They feel that this situation yields for cooperation rather than forcing their way in.
- Conservative behavior: Conservative drivers are not likely to perform forced merge, as they would wait for a substantive gap to form; older drivers might fall in this category. However, no such behavior was identified from the focus group, as the sample did not include older drivers.

Lastly, the case that involves freeway vehicles' willingness to give way to a ramp merging vehicle under congested conditions showed a small differentiation among participants' responses. The following categories are drawn from this case:

- Aggressive behavior: Drivers are not willing to let any vehicle in. All participants reported that they do not react in this manner, however, they have seen such behaviors from others.
- Average behavior: Drivers are not willing to let more than one vehicle in.
- Conservative behavior: Drivers may let one or two vehicles in. High probability of giving way to the merging vehicles.

Table 4-5 summarizes the results related to behavioral categories of the participants for each question (columns 1 to 4). This table also presents participants' responses from the background survey. As shown in columns 1 to 4, the same participant might exhibit different degrees of aggressiveness depending on the situation. For example, under dense traffic, a ramp driver that hesitates to perform a forced merge (conservative behavior – column 2), might become aggressive under congested traffic (aggressive behavior – column 3). Likewise, in dense traffic, the same driver may be equally or more aggressive when they are on the freeway than when they are the merging vehicle. This may be explained by the fact that ramp vehicles do not have the right-of-way or speed advantage compared to the freeway vehicles, thus, they seem to feel less entitled to receive priority. Freeway vehicles are more likely to change lanes than decelerate to accommodate a merging vehicle. Another significant result is that congested conditions yield less variability in driver behavior. Under these conditions, ramp vehicles will

either force their way in, or they will wait for the freeway vehicle to yield, and freeway vehicles become more accommodating and are willing to let at least one vehicle to merge in front of them.

Cross-tabulation between gender and behavioral categories shows that, in dense traffic conditions, men appear to be more aggressive than women (Table 4-5). Also, there are inconsistencies regarding drivers' stated aggressiveness between the focus group results and the background surveys. For example, drivers that indicated they consider themselves as 'somewhat aggressive' in the background survey did not show any indication of aggressiveness based on their responses during discussion.

Table 4-5. Behavioral categories based on focus group scenarios and background survey form

ID	Behavioral categories				Background survey responses				Pre-screening	
	Dense traffic Start coop. (1)	Start forced (2)	Congested traffic Start forced (3)	Yield forced (4)	Speed (mi/h) (5)	Lane change frequency (6)	Driver type (7)	Driver type by friends (8)	Gender (9)	Age group (10)
1_03	Av	C	Av	C	70-75	Sometimes	V.C.	V.C.	Female	25-35
1_05	Av	Av	Ag	C	70-75	Sometimes	S.C.	S.C.	Male	25-35
1_09	Ag	Av	Ag	C	65-70	Very often	S.A.	S.C.	Male	45-55
1_22	Av	Ag	Av	C	75-80	Very often	S.A.	S.C.	Male	25-35
1_01	Av	Av	Av	C	75-80	Sometimes	S.A.	S.A.	Female	25-35
1_15	Av	Av	Ag	C	65-70	Very often	S.A.	S.A.	Female	25-35
2_13	Av	C	Ag	Av	75-80	Sometimes	S.A.	S.A.	Female	55-65
2_12	Av	Av	Av	C	75-80	Very often	S.A.	S.A.	Female	35-45
2_16	Ag	C	Ag	C	>80	Very often	S.A.	S.A.	Female	18-25
2_07	Ag	Ag	Ag	Av	75-80	Sometimes	S.A.	V.A.	Male	18-25
2_25	Av	Av	Ag	Av	70-75	Very often	S.C.	V.C.	Female	35-45
3_26	Av	C	Av	C	70-75	Seldom	S.C.	V.C.	Male	35-45
3_04	Av	Av	Ag	C	>80	Sometimes	S.A.	S.C.	Male	18-25
3_06	Ag	Ag	Ag	C	75-80	Very often	S.A.	S.A.	Male	18-25
3_14	Av	Av	Av	C	65-70	Sometimes	S.A.	S.A.	Male	35-45
3_27	Av	C	Av	C	65-70	Very often	S.C.	S.A.	Female	55-65
3_28	Av	C	Av	C	75-80	Very often	S.A.	S.A.	Female	25-35

C: Conservative, Av: Average, Agr: Aggressive

V.C.: Very conservative, S.C.: Somewhat conservative, S.A.: Somewhat aggressive, V.A.: Very Aggressive

Other Observations

Five participants indicated that urgency might cause them to accept smaller gaps. The remaining responded that urgency would affect their speed selection and lane-changing activity on the freeway, but not the way they merge. With respect to the trip purpose, many participants responded that for casual driving, they drive more relaxed compared to commuting.

The last question entailed differences in driving alone vs. having passengers. Many participants stated that they are more cautious when they have passengers, because they feel responsible for them. Conversely, they drive faster when they drive alone. However, if they are involved in a conversation they are less focused and more distracted.

Conclusions

Several important conclusions were drawn from the focus group study:

- Participants' responses were uniform with respect to the steps involved in merging, both for non-congested and congested conditions.
- Ramp design appears to affect drivers' merging process. Most of the participants indicated they would speed up and be more aggressive on taper ramps, compared to parallel design.
- Regarding gap acceptance, the participants would likely react differently, depending on which factors each one considers. Some drivers (14 out of 17) indicated that they might choose any gap (adjacent, upstream, or downstream), depending on the traffic conditions, while others (3 out of 17) would be less flexible. This searching and targeting of the surrounding gaps has also been described in Toledo (2003). Variables that affect gap acceptance have also been identified.
- Discussion on vehicle interactions showed that, if participants are on the freeway, their preference is to change lanes and avoid decelerating. If this cannot be accomplished, they will cooperate, depending on the speed/acceleration of the ramp vehicle, and its size/type. If the ramp vehicle attempts to force its way in, they will consider their distance to the upstream vehicle and the relative speed with the adjacent lane to decide whether to decelerate or change lanes. Ramp vehicle's decision to initiate a forced merge depends mostly on traffic-related factors, such as freeway speed, congestion and gap availability.
- Although the discussions captured a significant variability among participants', it is likely that their reported actions are different than their actual actions, depending on the values of each individual. For example, someone who values aggressiveness might respond as if he/she is aggressive.

- The stated driver actions were analyzed to identify differences in driver behavior. The criterion of “selfishness” was used to develop three behavioral categories: aggressive, average and conservative. Given this definition, the degree of aggressiveness of each driver varies as a function of their task and the traffic conditions.
- In congested conditions, driver behavior displays less variability; therefore, it may be more predictable. This is consistent with findings (Persaud and Hurdle, 1991; Cassidy and Bertini, 1999) indicating that the mean queue discharge flow displays smaller variability than other capacity-related measures, and remains consistent from day to day.

The following recommendations are offered:

- The merging process solicited by focus group participants should be considered in developing or refining existing analytical or simulation models for freeway operations. Similarly, the factors stated as contributing in gap selection should be considered when developing or revising gap acceptance models.
- Differences in attitudes and driver behavior between non-congested and congested conditions should be explicitly incorporated in traffic operational models.

CHAPTER 5

FIELD DATA COLLECTION

This chapter presents the second part of the data collection effort for this research. The focus of the field data collection is to quantify the effect of individual driver characteristics on their merging decisions and associate those with the breakdown occurrences at the freeway-ramp junctions. The data collection undertaken for this task entails observations of participants driving an instrumented vehicle and simultaneous video observations of the freeway during these experiments. All survey instruments as well as the methodology used for the field experiments were pre-approved by the Institutional Review Board (IRB) of the University of Florida. This chapter describes the formulation of the instrumented vehicle experiments and the simultaneous collection of traffic data, and presents findings and results related to the field observations of the merging process.

In-Vehicle Data Collection

The following section provides information on the organization and the setup of the instrumented vehicle experiment. The section also provides a description of the methods used for the data collection as well as the selection of the participants. Procedures used to process the in-vehicle data are also discussed.

Description of Instrumented Vehicle

The instrumented vehicle used in this study is a Honda Pilot SUV, owned by the University of Florida – Transportation Research Center (TRC). The vehicle is equipped with a Honeywell Mobile Digital Recorder (HTDR400) system. The vehicle has an inbuilt GPS where all information about vehicle position and speed data is displayed and recorded on the HTDR400. In addition to the GPS unit, the vehicle includes four wide coverage digital cameras (DCs) that capture video clips facing the front, the back and the two sides of the vehicle. The

video data, as well as audio data during the driving task, are recorded on the HTDR400, and stored at a local hard drive that is located at the trunk of the vehicle. An additional camera facing the driver was installed on the dashboard, to capture facial reactions of the driver during the experiments. An internal view of the instrumented vehicle is shown in Figure 5-1. The data collected directly through the instrumented vehicle include:

- Instrumented vehicle geographical position, speed, throttle, and left-right turn signal activation.
- Video clips of the vehicles in front, behind and adjacent to the instrumented vehicle.
- Audio recordings during the driving task.

A laptop was connected to the system which allows for reviewing the display of all four cameras, through the HTRD BusView software. All video clips were downloaded from the hard drive to the laptop shown in Figure 5-1 for further analysis.



Figure 5-1. Inside view of the TRC instrumented vehicle.

Driving Routes

The exact routes that the participants followed for both AM and PM peak periods are illustrated in Appendix B. Each participant would conduct two loops during the AM routes and three during the PM routes.

These routes were developed after selecting the appropriate freeway-ramp junctions that meet the following criteria:

- The ramp junctions experience mild to heavy traffic during AM and/or PM peak periods.
- The total travel time for the routes does not exceed the expected duration of the in-vehicle experiment, which is approximately one hour, including the required stop for discussion with the participants.
- The routes are not too complex so that the participants would not be confused during their driving.
- Cameras from the Jacksonville Traffic Operations Center should be available at these ramp junctions. The cameras' field of view should meet the respective criteria for the concurrent field data collection, as presented in the following section.
- These locations should be free from construction work, as this may affect the driving task of the participants, as well as the data quality obtained from the detectors.

The final routes consist of four consecutive ramp junctions along I-95. The locations of those junctions are at: (i) I-95 NB @ Phillips Hwy, (ii) I-95 NB @ Baymeadows, (iii) I-95 NB @ WB J.T. Butler, (iv) I-95 SB @ Bowden, and (v) I-95 SB @ J.T. Butler EB. The participants would also drive through the J.T. Butler junction both in the SB and NB direction.

Geometry of the Freeway Ramp Junctions

The selected ramp junctions have different designs, concerning the acceleration lane type and the overall length. Two ramps are tapered and the remaining four are parallel type. All distances are measured from the gore area until the end of the solid white line, the end of the dashed line and the end of the acceleration lane. The dimensions of the two tapered ramps at J.T. Butler SB and NB approaches are illustrated in Figure 5-2.

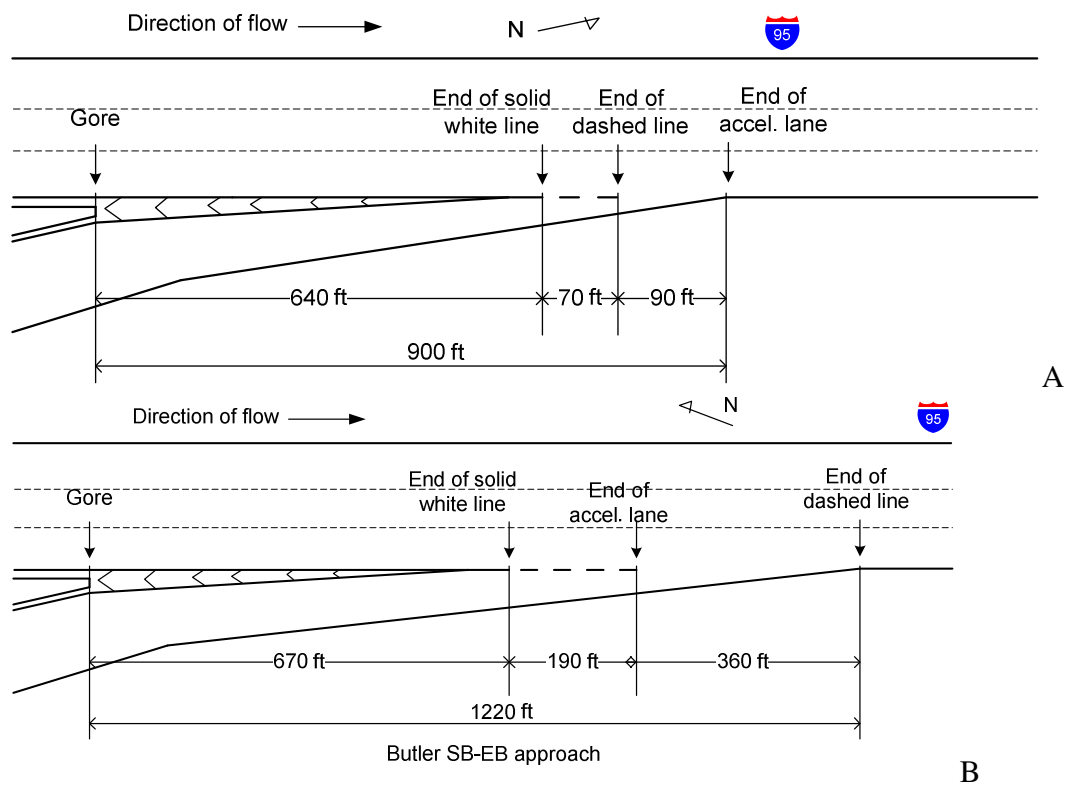


Figure 5-2. Geometric characteristics of tapered entrance ramps on I-95 at A) J.T. Butler NB-WB approach, and B) J.T. Butler SB-EB approach.

Figure 5-3 shows the dimensions of the three parallel ramps. The total length of the acceleration lane ranged from 900 ft to 1,530 ft. All locations have three lanes, except the junction at Phillips Highway NB which has four lanes.

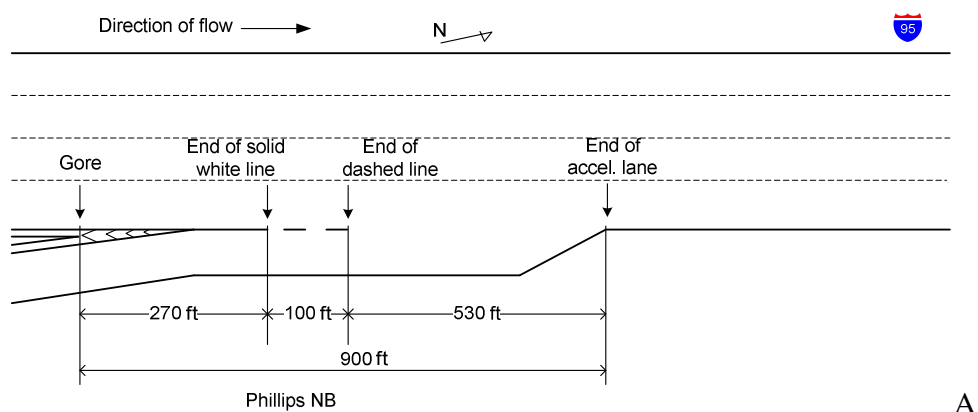


Figure 5-3. Geometric characteristics of parallel entrance ramps on I-95 at A) Phillips NB, B) Baymeadows NB, and C) Bowden SB.

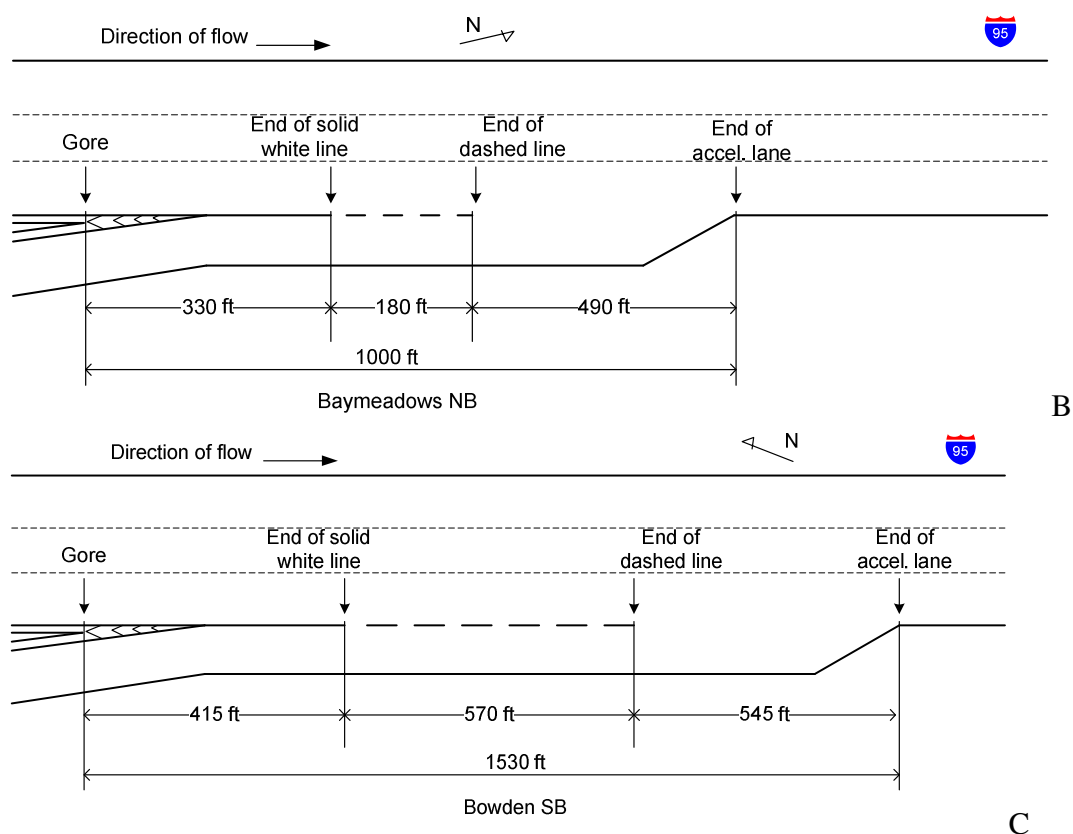


Figure 5-3. Continued.

Selection of Participants

The instrumented vehicle experiment was advertized through the internet and local organizations in Jacksonville, FL, and candidates were provided a description of the driving routes and a pre-screening questionnaire. The questionnaires assembled information on gender, age-group, ethnicity, years of driving experience, occupation, frequency of driving and time of day, and vehicle type, similar to those used for the focus group experiment. The information was used to select a diverse set of participants. Although the targeted number of participants was sixty, many candidates would fail to appear at the meeting location without earlier notification, resulting in misspent of time and resources at the expense of the experiment. Therefore, only thirty-one participants eventually completed the experiment. The demographics of the participants are presented in Table 5-1.

Similar to the focus group experiment, the participants completed a background survey form, which contained seven multiple-choice questions related to their driving habits. These questions solicited the subjects' desired freeway speed (assuming good visibility and weather conditions and a 70-mi/h speed limit), lane-changing habits, how aggressive they consider themselves, how aggressive their friends/family consider them, when and where they typically merge onto the freeway, how they react if a vehicle merges onto the freeway while they are driving on the right-most lane, and whether they plan their trips allowing for additional time to mitigate possible delays.

Table 5-1. Demographic characteristics of instrumented vehicle experiment participants

ID	Gender	Age group	Race	Experience	Occupation	Driving frequency	Hours per week	Peak/non-peak	Vehicle ownership
10	Male	55-65	Caucasian	>=10 years	Retired Military	Everyday	4-8 hrs	Peak	Pickup/SUV
47	Male	25-35	Caucasian	>=10 years	Clerk	Everyday	8-14 hrs	Peak	Sedan/Coupe
49	Male	18-25	Caucasian	3-9 years	Full Time Student	Everyday	<4 hrs	Peak	Sedan/Coupe
52	Male	25-35	Caucasian	>=10 years	Professional driver	Everyday	4-8 hrs	Peak	Pickup/SUV
63	Male	25-35	Caucasian	>=10 years	Full Time Student	Everyday	8-14 hrs	Peak	Pickup/SUV
65	Male	25-35	Caucasian	>=10 years	Safety Ranger	Everyday	<4 hrs	Peak	Sedan/Coupe
69	Female	25-35	Afr/ American	>=10 years	Full Time Student	Everyday	4-8 hrs	Peak	Pickup/SUV
71	Female	18-25	Asian-Caucasian	3-9 years	Customer Service	Usually	4-8 hrs	Peak	Sedan/Coupe
72	Male	25-35	Caucasian	>=10 years	Property Manager	Everyday	8-14 hrs	Peak	Sedan/Coupe
73	Female	45-55	Caucasian	>=10 years	Office Manager	Everyday	<4 hrs	Peak	Sedan/Coupe
76	Male	25-35	Caucasian	>=10 years	University Staff	Never	<4 hrs	Non-peak	Sedan/Coupe
23	Male	45-55	Caucasian	>=10 years	Military	Usually	4-8 hrs	Peak	Pickup/SUV
27	Male	45-55	Caucasian	>=10 years	Qual. Assurance	Everyday	8-14 hrs	Peak	Sedan/Coupe
32	Male	55-65	Caucasian	>=10 years	Pilot	Sometimes	4-8 hrs	Non-peak	Sedan/Coupe
37	Female	45-55	Caucasian	>=10 years	Housewife	Everyday	4-8 hrs	Non-peak	Pickup/SUV
51	Female	25-35	Caucasian	>=10 years	Admin. Assistant	Everyday	4-8 hrs	Peak	Pickup/SUV
59	Male	18-25	Asian	1-3 years	Full Time Student	Never	<4 hrs	Non-peak	Sedan/Coupe
60	Male	45-55	Caucasian	>=10 years	Police Officer	Everyday	8-14 hrs	Peak	Sedan/Coupe
61	Male	25-35	Caucasian	>=10 years	PC Refresh Manager	Everyday	8-14 hrs	Peak	Sedan/Coupe
67	Male	35-45	Afr/ American	>=10 years	Cook	Everyday	8-14 hrs	Non-peak	Sedan/Coupe
68	Female	18-25	Caucasian	1-3 years	Full Time Student	Everyday	4-8 hrs	Peak	Sedan/Coupe
74	Female	45-55	Caucasian	>=10 years	Internet Business	Usually	8-14 hrs	Peak	Sedan/Coupe
17	Female	45-55	Afr/ American	>=10 years	Secretary	Everyday	8-14 hrs	Peak	Sedan/Coupe
18	Female	35-45	Caucasian	>=10 years	Officer	Everyday	>14 hrs	Peak	Sedan/Coupe
19	Female	45-55	Caucasian	>=10 years	Admin. Assistant	Everyday	<4 hrs	Peak	Pickup/SUV
50	Female	25-35	Caucasian	>=10 years	Housewife	Everyday	4-8 hrs	Peak	Pickup/SUV
56	Male	35-45	Afr/ American	>=10 years	Sales	Everyday	8-14 hrs	Peak	Sedan/Coupe
58	Male	18-25	Caucasian	3-9 years	Full Time Student	Everyday	8-14 hrs	Peak	Sedan/Coupe
66	Male	35-45	Asian	1-3 years	Drafter	Everyday	<4 hrs	Non-peak	Pickup/SUV
70	Male	45-55	Caucasian	>=10 years	Professional Driver	Everyday	>14 hrs	Peak	Sedan/Coupe
75	Female	55-65	Caucasian	>=10 years	Sales & Marketing	Usually	8-14 hrs	Peak	Sedan/Coupe

Data Collection Procedures

Participants of the instrumented vehicle experiment were requested to drive the vehicle along the pre-selected routes on the Jacksonville area, with the presence of the investigator and an assistant. The participants were driving on I-95 in the northbound and southbound directions, during near-congested and congested conditions in AM and PM peak periods. Two experiments would run during the morning peak period (7:00-8:00 AM and 8:15-9:15 AM) and three during the evening peak period (3:00-4:00 PM, 4:15-5:15 PM and 5:30-6:30 PM). To examine driver behavior at merging segments, participants were asked to enter the freeway from specific on-ramps and also stay on the mainline, passing through other ramp merging sections multiple times. In this way, both behaviors of the “ramp-merging vehicle” and the “through vehicle” for the same driver were captured.

In such behavioral studies it is essential to have feedback from the participants, to record and understand what their stimuli and possible intentions or reactions are, during the driving task. However, it is not advantageous to ask the participant questions during their driving, because this will not only distract them from the driving task, but it may also create a feeling of “being observed”, which will contribute to a change in their behavior and thus, result in biased conclusions. To reduce that bias, the investigator and the assistant were sitting at the back seat of the instrumented vehicle, so that the participant would not feel that he/she is being observed. In addition, participants were asked to drive as they normally would, and they were given no guidance with respect to their lane selection. Also, all questions and discussion regarding the driving of the participants were done after each route is completed, where the vehicle were stopped for five to ten minutes. The completion time of all routes was approximately one hour.

During the driving task the participants were asked to inform the investigator whenever they have an intention to merge or change lanes, and to identify the desired gap with respect to

the freeway vehicles, if such issue would emerge. Participants were also asked to report perceived actions of cooperation from the other vehicles primarily during the merging maneuver. After the completion of each route, participants were asked to explain their thinking process that pertains to specific actions that occurred during the experiment, if this was not reported while driving.

In-Vehicle Data Processing

This section describes the methods used for the estimation of the model parameters. The video data collected from the instrumented vehicle mounted cameras were used to estimate parameters related to relative distances and speeds. Still images were extracted from both front and rear videos at a 0.5 sec time resolution. When participants were merging into the freeway, the image extraction would start as soon as the vehicle entered the acceleration lane until it had completed the merge. When participants were driving on the freeway, the extraction would start at least 2-3 seconds before they indicated their intention to react to the merge vehicle. Along with the extracted frames, the instrumented vehicle speed and longitude/latitude data were recovered from the GPS. The following subsections present the processing techniques of the collected data.

Gaps with adjacent vehicles and gap change rates

The gaps between the subject vehicle and its adjacent vehicles were estimated for each consecutive frame. Appendix C describes the method applied for measuring distances from still images. In addition, the gap change rates were estimated every 0.5 seconds, throughout the trajectory of the vehicles. The gap change rates represent a measure of the relative speeds and accelerations of the two vehicles. These were evaluated every 0.5 seconds, throughout the entire observed trajectory of the vehicles.

Speeds and accelerations

The speeds of either the lag, lead or ramp vehicles are estimated through consecutive frames using the equations of motion. Average speeds and accelerations are estimated every second. The speeds of the subject vehicle are obtained directly from the GPS, whereas the accelerations are calculated as the speeds change rate, and evaluated at a one-second resolution.

Vehicle positions

Through the GPS information the exact position of the subject vehicle is obtained. This position is referenced relative to fixed points in the vicinity of the ramp junction. Usually, the end of the solid white line of each acceleration lane was used as the reference point.

Average density and freeway speed

Density was calculated from snapshots of the merge area, taken from the TMC cameras, at the time the instrumented vehicle would enter or drive through. Density was measured as the total number of freeway vehicles within a segment that ranged from 500 to 1400 ft long depending on the site. The density measures were transformed to equivalent vehicles per mile and then averaged across the travel lanes. The average freeway speed of the right-most lane was obtained from the 1-minute RTMS data, at the time that the instrumented vehicle was at the subject ramp junction.

Data Collection at the Jacksonville TMC

Concurrently with the instrumented vehicle experiment, traffic-related data were collected. More specifically, with the collaboration of the Jacksonville Traffic Operations Center, the selected traffic monitoring cameras become available during the experiment. The Traffic Operations Center also provided two video feeds to record the video data. An assistant located at the Traffic Operations Center would switch interchangeably the connection between the cameras and the communication channels, to capture the instrumented vehicle at each freeway-ramp

merge location it was going through. In addition, traffic-related data collected from the remote traffic microwave sensors (RTMSs) were also available through the Steward Data Warehouse. The data that are available through the Steward Data Warehouse are per lane freeway volume, speed, and occupancy.

As shown in Figure 5-4 there are several cameras placed along I-95 used by the Jacksonville Traffic Operations Center for traffic monitoring. Since the cameras were used for both the selection of the routes for the in-vehicle experiment, and the concurrent field data collection, the following selection criteria were developed:

- Clear view of the incoming traffic from the freeway and the ramps should be available.
- Locations should be free of construction work, because at those locations the RTMSs are not calibrated, and that would impact the validity of the data.

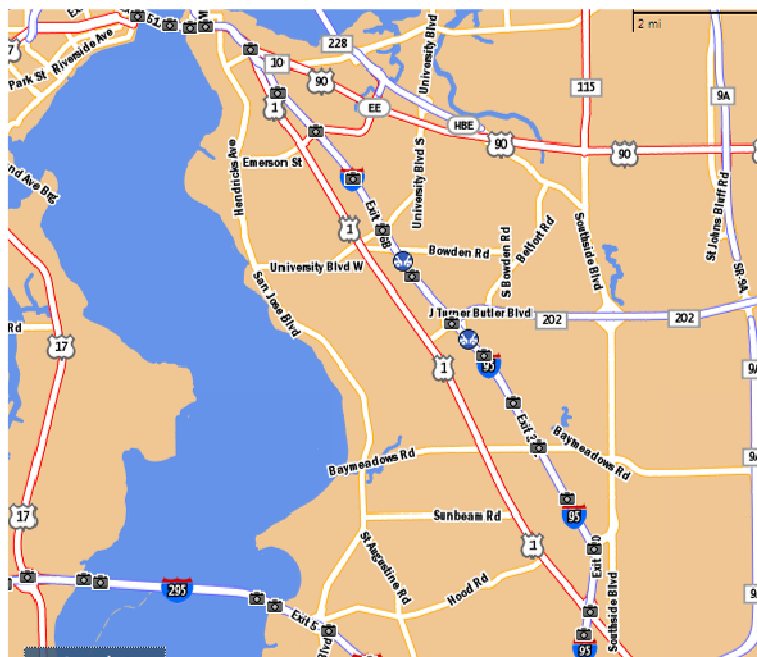


Figure 5-4. Location of available cameras along I-95.

Figure 5-5 provides video snap-shots of four of the five merging segments used in this study. The TMC cameras face both northbound and southbound travel directions.



Figure 5-5. Camera field of view along I-95 A) Phillips Hwy (facing NB), B) Baymeadows (facing NB), C) Bowden (facing SB) and D) J.T. Butler (facing SB).

It should be noted that, in the event of an incident, the assistant could not have access to the cameras, as these are also operated by the Highway Patrol officers. Such instances did occur during the data collection periods, and therefore, the respective videos were not recorded. Also, due to extended congestion resulting from these incidents, the routes were adjusted to complete the experiment on time. In both cases participants would use the I-95 SB entrance from J.T. Butler WB approach, which is a loop ramp. Of course, video recordings from this ramp were not available, since the TMC cameras were not adjusted for that location.

TMC Data Processing

The merge junctions that experience breakdown events due to merging operations were evaluated using the RTMSs data. Speed time-series plots at all detector stations along the freeway segment were constructed, for all days of the data collection. Visual observations of the

time-series revealed the breakdown locations and times during the AM and the PM peak periods. The breakdown events that were observed during the data collection days occurred at NB junction of I-95 with J.T. Butler Boulevard. Other breakdowns were also observed at the SB off-ramp at J.T. Butler; however this was due to the off-ramp queue spilling back on the freeway. Non-recurrent congestion due to an incident was observed at the SB junction of I-95 with J.T. Butler. Also, congestion starting from the I-95 NB junction with J.T. Butler would propagate further upstream at the junction with Baymeadows, and even reaching the junction with Phillips Highway NB. At the southbound direction, congestion would start sometimes at the on-ramp from J.T. Butler EB approach, and sometimes at the SB exit at J.T. Butler. Breakdowns from those locations would typically propagate congestion further upstream up to the junction with Bowden Road.

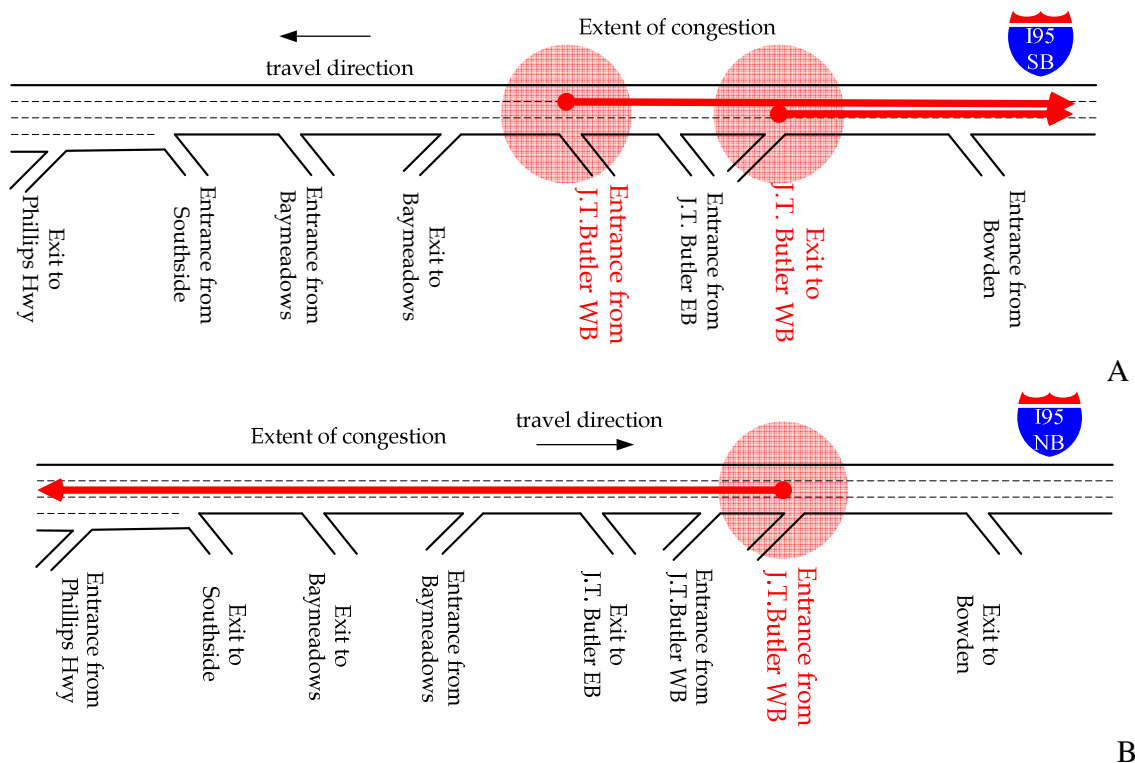


Figure 5-6. Observed breakdown locations and congestion propagation along I-95 A) SB direction, and B) NB direction.

Next, the time-series were compared with the times of the TMC video recordings at each location. Depending on the prevailing traffic conditions, observations were grouped into the following five traffic states:

- Non congested period (173 observations),
- Before breakdown on-ramp events at NB or SB J.T.Butler (6 observations),
- Before breakdown off-ramp events at SB J.T.Butler (1 observation),
- Before congestion starts at the remaining locations (10 observations),
- Within congested period for all locations (10 observations).

The video recordings before the breakdown events provide information about the merging maneuvers and the lane changing activity that contributed to the occurrence of the breakdown.

These recordings were used to develop the merging turbulence model, by counting at each minute the number of interacting merging maneuvers (cooperative or forced) and the number of lane changes that caused vehicles to decelerate. Additional causes of decelerations were observed and recorded as well. Sometimes, decelerations on the right lane due to merging would cause drivers on the middle lane to decelerate. Also, decelerations past the merge area and inside the bottleneck were observed, which indicated vehicles' effort to discharge. Usually, these decelerations became more frequent, forcing the incoming traffic on the freeway to decelerate as well, thus, creating a wave of decelerations moving upstream. After that, it was clear that merging was not the reason for decelerating – people would still decelerate even if there was no vehicle on the on-ramp. During those intervals, the merging process of the ramp vehicles would become more difficult, and they would start to form queues on the on-ramp. Examination of the speeds during that minute would reveal that the speed decrease (i.e., speed-flow breakdown) has initiated.

Field Experiment Results

Overview of the Observed Merging Process

As part of the field experiment, the participants were asked to put into words their thoughts as they were driving on the on-ramp and approaching the merge. Generally, the field observed merging process is quite similar with that identified during the focus group discussions. The following steps summarize the observed merging process:

- Step 1: Participants start accelerating on the on-ramp and first think about merging when they have a clear view of the freeway traffic.
- Step 2: Participants evaluate the speed and the flow of traffic on the freeway, to assess how much they should adjust their own speed. They also account for the presence of other on-ramp vehicles ahead. If traffic is free-flowing, participants leave a large gap to use later for acceleration. If the freeway is congested, they do not leave a large gap.
- Step 3: Participants accelerate to a speed close to the freeway speed as they reach the acceleration lane. They also start looking at potential gaps.
- Step 4: This step includes the gap acceptance and merging process. In free-flowing conditions participants adjust their speed if necessary to fit a gap. Tasks such as actuating the turn signal and checking of the mirrors or blind spots follow. In congested conditions, drivers anticipate cooperation from the freeway vehicles.
- Step 5: After merging, most of the participants move to the middle lane unless they need to exit at the next junction.

Distinction of Merging Maneuvers

As it was also discussed in Chapter 4, the merging maneuvers are categorized to free, cooperative and forced merges, depending on the degree and the type of observed interaction between the ramp vehicle and the freeway lag vehicle. Generally, a free merge does not involve any interaction between the two vehicles. In a cooperative merge the freeway vehicle decides to yield to the ramp vehicle by either decelerating or changing lanes. In a forced merge, it is the ramp vehicle that initiates the maneuver and the freeway vehicle reacts to that by either decelerating or changing lanes.

The distinction of the merging maneuvers when the participants were driving on the freeway was done considering their narratives as they were approaching the merge area. When the participants were the merging vehicle, there was no “inside” information about the freeway drivers’ intended actions. In these cases, the distinction of the maneuvers was done using the TMC video data and observing the brake lights of the freeway vehicle or its trajectory.

However, when drivers decide to provide cooperation (e.g., decelerate) towards the merging vehicle, they will do so well in advance. As such, their deceleration is not always captured by the TMC cameras, due to limitations of the cameras’ field of view. In this case, the distinction of the maneuver was done by measuring the gap and its change rate with the lag using the rear in-vehicle camera. If the lag gap was relatively constant as soon as the ramp vehicle enters the on-ramp and starts to increase, it suggests that the two vehicles had similar speeds but the lag vehicle decelerated to increase the gap. If the gap was decreasing, but with a decreasing rate, this suggests that the lag vehicle speed was higher than the ramp vehicle speed, and as soon as it decided to yield the gap was decreasing at a lesser rate. As such, at the time the ramp vehicle is merging, the gap will remain relatively constant; indicating that no further speed adjustment is required (equalized speeds). In forced merging the gap remains constant or it is narrowing as the ramp vehicle is traveling on the on-ramp, but it starts to increase or to decrease with a diminishing rate as soon as the ramp vehicle initiates the merge. After the maneuver is complete, the gap may continue to increase indicating that the lag needs to prolong the deceleration to further adjust its speed.

In summary, the definitions of the three types of merging maneuvers considering vehicle interactions are:

- Free merge: there is no apparent interaction between the ramp vehicle and the freeway lead or lag.

- Cooperative merge: the lag decelerates or changes lanes to allow the ramp vehicle to enter. If the lag decides to cooperate by decelerating, the gap between the lag and the ramp vehicle will be increasing or decreasing with a diminishing rate as soon as the ramp vehicle enters the on-ramp and it remains relatively constant as the ramp vehicle is merging.
- Forced merge: the ramp vehicle initiates the merging maneuver and the lag responds by either decelerating or changing lanes. In this case the gap between the lead and lag is either constant or narrowing (lag maintains speed or accelerates) before the initiation of the merge, and starts to increase or decrease with a diminishing rate as the ramp vehicle enters. After the merge the gap continues to increase.

The total number of merging maneuvers that the participants performed as the ramp vehicle was 273 and 109 as the through vehicle. These maneuvers refer to non-congested conditions. Table 5-2 summarizes the types of merging maneuvers that the participants encountered as both the ramp merging and the freeway through vehicle at each merge junction. It also provides the percent of decelerations or lane changes performed due to vehicle interactions.

Table 5-2. Merging maneuver categories

Ramp Junction	Free	Cooperative	Forced
Ramp merging vehicle			
Baymeadows NB	59	22	5
Bowden SB	43	34	6
JTButler NB	9	6	2
JTButler SB	56	7	3
Phillips NB	13	4	4
Total	180	73	20
% decelerations	-	70%	100%
% lane changes	-	30%	0%
Freeway through vehicle			
Baymeadows SB	19	0	0
JTButler NB	50	28	0
JTButler SB	18	2	0
Total	87	30	0
% decelerations	-	30.4%	-
% lane changes	-	69.6%	-

Table 5-2 shows that the participants performed all types of merging maneuvers, the majority of which were free maneuvers. When participants received cooperation, usually it was through deceleration rather than lane changing. However, it is possible that cooperative lane

changing maneuvers were not captured, neither from the TMC cameras nor from the in-vehicle cameras, given that these maneuvers typically occur further upstream of the merge area. In this case, these would be categorized as free merging maneuvers. When the participants performed forced merging maneuvers, the reaction of the freeway vehicles was to decelerate in all cases.

Table 5-2 also shows that there were observations where participants provided cooperation towards ramp vehicles. Usually, participants would move to the inside lane to accommodate the ramp vehicles, and less frequently they would decelerate. This finding is also consistent with the results from the focus group discussions, presented in Chapter 4. Lastly, the participants did not incur any forced merging maneuver.

Driver Behavior Types

The data obtained through the in-vehicle experiment allow for investigating differences and similarities between the drivers and examining how the variability in driver behavior affects traffic operations during merging. This section describes the identification of driver behavior for each participant involved in the experiment. Three types of driver behavior were considered: aggressive, average and conservative behavior. For this task, the actual observed driver behavior was evaluated considering both qualitative assessment based on the focus group analysis, and quantitative factors based on the field observations.

The qualitative assessment applies the criterion of “selfishness” for each participant throughout the entire duration of their driving task. Drivers that exhibit high degree of selfishness and consider primarily their own status on the road are regarded as aggressive. For example, aggressive drivers are unwilling to yield to ramp vehicles, and they dislike being cut off; however they are very likely to impose to other vehicles by forcing them to decelerate. Drivers that act primarily as a response to the other vehicles’ actions are considered to be conservative. Conservative drivers show increased hesitation when merging and they are very

likely to yield to a ramp merging vehicle. Drivers that consider both their own status but also the effect of their actions to the other vehicles are categorized as average. Average drivers are equally likely to show cooperation towards a ramp vehicle depending on the traffic conditions. These drivers also do not exhibit any characteristics that could describe them as either aggressive or conservative.

The quantitative assessment was based on two criteria (AAA, 2009): (i) number of discretionary lane changes and (ii) observed speeds when driving under free-flowing and not car-following conditions. Given the design of the experiment (i.e., frequent exits from the freeway), participants had generally limited opportunities for performing discretionary lane changes and for driving at the inside (faster) lanes. As such, participants that performed up to two lane changes and/or followed a speed up to 5 mi/h the speed limit were considered to be conservative. Participants that performed up to five lane changes and/or drove at a speed up to 10 mi/h over the speed limit were considered to be average. Participants that performed at least six lane changes and/or drove at high speeds up to 15 mi/h over the speed limit (or 10 mi/h over the limit under raining conditions) were grouped as aggressive.

The driver behavior types are intended to investigate primarily vehicle interrelations and traffic operations, and this is addressed in both quantitative and qualitative criteria. Therefore, the definition of aggressive behavior presented here does not include characteristics such as increased risk to collision or drivers' noncompliance, which are typically used to examine the effects of driver behavior on traffic safety.

In summary, the characteristics of the three behavioral types based on both the quantitative and the qualitative assessment are:

- Aggressive behavior: participants do not hesitate to cut somebody off when merging. They have a sense of pressure and eagerness to get in, and not run out of space. Participants

perform at least six discretionary lane changes and/or drive at speeds up to 15 mi/h over the speed limit (or up to 10 mi/h in raining conditions).

- Average behavior: participants' driving behavior depends equally on their own status and the surrounding traffic conditions. They perform up to five discretionary lane changes and/or drive up to 10 mi/h over the speed limit.
- Conservative behavior: participants will not perform a forced merge and they will wait for a large gap to merge without disrupting the traffic. They might decelerate significantly to allow a vehicle to merge. They also perform up to two discretionary lane changes and/or their speed is up to 5 mi/h over the speed limit.

Table 5-3 summarizes the results of the driver behavior analysis for all participants. This table also includes their background survey responses on their degree of aggressiveness as this is perceived by themselves and by their friends or family, their stated driving speed and lane changing activity.

Table 5-3. Driver behavior types based on actual observations and background survey form

Field Observations				Background Survey Responses			
ID	DLC	Driving speed	Driver type	Lane changing	Driving speed	Aggressiveness	Aggressiveness by others
10	7	77 mi/h	Aggressive	Very often	75 to 80 mi/h	Somewhat aggressive	Somewhat aggressive
47	5	71 mi/h	Aggressive	Very often	70 to 75 mi/h	Somewhat aggressive	Somewhat conservative
49	16	72 mi/h	Aggressive	Very often	70 to 75 mi/h	Somewhat aggressive	Somewhat aggressive
52	6	68 mi/h (Rain)	Aggressive	Very often	70 to 75 mi/h	Somewhat aggressive	Somewhat aggressive
63	12	78 mi/h	Aggressive	Sometimes	70 to 75 mi/h	Somewhat conservative	Very conservative
65	9	79 mi/h	Aggressive	Very often	75 to 80 mi/h	Somewhat aggressive	Somewhat aggressive
69	16	67 mi/h (Rain)	Aggressive	Sometimes	70 to 75 mi/h	Somewhat conservative	Very conservative
71	7	75 mi/h	Aggressive	Sometimes	70 to 75 mi/h	Somewhat conservative	Somewhat aggressive
72	7	78 mi/h	Aggressive	Very often	70 to 75 mi/h	Somewhat aggressive	Somewhat aggressive
73	6	77 mi/h	Aggressive	Very often	>80 mi/h	Somewhat aggressive	Very aggressive
76	6	79 mi/h	Aggressive	Very often	75 to 80 mi/h	Somewhat aggressive	Somewhat conservative
23	4	68 mi/h	Average	Very often	70 to 75 mi/h	Somewhat conservative	Very conservative
27	5	68 mi/h	Average	Sometimes	75 to 80 mi/h	Somewhat aggressive	Somewhat aggressive
32	4	71 mi/h	Average	Sometimes	75 to 80 mi/h	Somewhat aggressive	Somewhat conservative
37	4	71 mi/h	Average	Sometimes	70 to 75 mi/h	Somewhat aggressive	Somewhat aggressive
51	4	75 mi/h	Average	Very often	75 to 80 mi/h	Somewhat conservative	Somewhat aggressive
59	5	68 mi/h	Average	Sometimes	70 to 75 mi/h	Somewhat aggressive	Very aggressive
60	4	71 mi/h	Average	Very often	70 to 75 mi/h	Somewhat aggressive	Somewhat aggressive
61	5	74 mi/h	Average	Very often	75 to 80 mi/h	Somewhat aggressive	Somewhat aggressive
67	4	73 mi/h	Average	Sometimes	75 to 80 mi/h	Somewhat conservative	Somewhat aggressive
68	4	70 mi/h	Average	Very often	70 to 75 mi/h	Somewhat conservative	Somewhat aggressive
74	4	72 mi/h	Average	Sometimes	70 to 75 mi/h	Somewhat conservative	Somewhat conservative
17	0	60 mi/h	Conservative	Sometimes	< 65 mi/h	Very conservative	Very conservative
18	2	70 mi/h	Conservative	Sometimes	70 to 75 mi/h	Somewhat conservative	Somewhat conservative
19	2	65 mi/h	Conservative	Sometimes	70 to 75 mi/h	Somewhat conservative	Somewhat conservative
50	2	71 mi/h	Conservative	Very often	70 to 75 mi/h	Very conservative	Somewhat conservative
56	2	67 mi/h	Conservative	Sometimes	70 to 75 mi/h	Somewhat conservative	Somewhat aggressive
58	2	71 mi/h	Conservative	Sometimes	70 to 75 mi/h	Somewhat conservative	Somewhat conservative
66	0	68 mi/h	Conservative	Sometimes	70 to 75 mi/h	Somewhat conservative	Somewhat conservative
70	2	69 mi/h	Conservative	Very often	70 to 75 mi/h	Somewhat aggressive	Very aggressive
75	1	70 mi/h	Conservative	Sometimes	70 to 75 mi/h	Somewhat conservative	Somewhat conservative

In summary, the field observations of driver behavior come in agreement with the quantitative criteria applied for the driver type distinction. The resulting categorization of drivers also provided a uniform allocation of all three types. However, there were differences between the field observed driver types and those stated at the background survey forms by the participants. For instance, some participants that regard themselves as conservative were found to be rather aggressive (e.g., participant #63, Table 5-3), whereas others that consider themselves aggressive, showed the exact opposite behavior (e.g., participant #70, Table 5-3). This inconsistency may be due to the fact that when asked about their perceived aggressiveness (or their friends/family perceived aggressiveness), people will respond by comparing themselves with their peers, thus their responses will not necessarily be objective.

Although the sample is not large enough to perform quantitative analysis on the driver type profiles, several qualitative conclusions can be drawn, by comparing this sample's demographics with the assigned driver type (Table 5-4).

Table 5-4. Demographic characteristics by driver behavior type

Driver Type	Male	Female	Average age group	Age group range
Aggressive	8 (73%)	3 (27%)	25-35	18-65
Average	7 (64%)	4 (36%)	35-45	18-65
Conservative	4 (44%)	5 (56%)	35-45	18-65
All	19 (61%)	12 (39%)	35-45	18-65

The average age group for the entire sample falls between 35 and 45 years old. The aggressive drivers are on the 25-35 years old group, whereas average and conservative drivers are on the older group (35-45). Also, the majority of men fall into the aggressive and average driver types, and women are more often found on the conservative driver type category.

Driver Decision-Making Process

The extraction of drivers' thinking process through the in-vehicle experiments is quite challenging, since drivers do not explicitly state their rationale behind their course of actions. However, some conclusions were drawn regarding their cooperation towards the merging vehicles. Based on the in-vehicle observations, drivers' decision-making is not necessarily a two-level process, where they decide first whether to provide cooperation or not, and then select the preferred action of cooperation. It was found that they would evaluate the situation considering all three alternatives (or two alternatives if lane changing was not an option) at the same level.

Summary and Conclusions

In this chapter the field data collection effort was discussed. The data obtained in this study contain concurrent observations of the behavior of thirty-one participants at ramp merge areas (both as the ramp and the freeway vehicle) and macroscopic observations of the traffic stream. Procedures for processing the raw data for further analysis are also presented in this chapter.

The following conclusions are offered based on the field observations:

- The steps involved in the observed merging process are found to be quite similar with that identified during the focus group discussions (Chapter 4), for both congested and non-congested conditions.
- When participants were on the freeway they were involved only in free and cooperative merging maneuvers, and not in forced merges. Participants would show cooperation through lane changing more often than through decelerating. This indicates drivers' preference to change lanes if a gap is available. This finding is consistent with the relevant discussion from the focus groups.
- When the participants were the merging vehicle the majority of observed merging maneuvers were free. Cooperative and forced maneuvers were observed as well. When drivers' received cooperation from the freeway vehicles, usually this was through deceleration rather than lane changing. However, it is possible that cooperative lane changes were not captured by the cameras since these would occur considerably upstream of the merge area. In this case they would be observed and characterized as free maneuvers.

- The participants' behavior was categorized as aggressive, average and conservative. Participants were categorized based on the criterion of "selfishness" as this was introduced in Chapter 4, and quantitative information about their speed and discretionary lane changing activity. Both assessments are consistent and come in agreement.
- There were few differences between the resulting driver type categorization and the participants' perceived aggressiveness. This inconsistency is most likely because participants responses may not be objective as will respond by comparing themselves with their peers.
- The resulting behavioral categorization showed that aggressive drivers belong to younger average age group category, compared to the other two types. Also, men were most likely to be aggressive than women.
- The field of view of the TMC cameras was very important for this study, as they dictate whether the locations of interest (e.g., bottlenecks) can be considered for data collection. However, there is a trade-off between the cameras field of view and the required zoom of the merge area to identify potential vehicle interactions and reactions. If more cameras were available, it would be possible to use multiple and capture the field of view with acceptable resolution upstream, at the merge and downstream of the merge area.
- The participation of actual drivers was probably the most challenging task of the data collection. This was primarily because several times drivers would fail to appear for the experiments, without any prior notification. In addition to that, obtaining drivers' thinking process was also challenging since drivers do not explicitly state their rationale behind their course of actions.

CHAPTER 6 MODEL DEVELOPMENT

This chapter presents the data analysis and estimation results that pertain to the models that describe ramp vehicles' gap acceptance decisions, through vehicles' deceleration decisions, and the probability of turbulence and breakdown using the field data. The first section explains the data used to model the ramp vehicle's gap acceptance decisions and presents the estimation specifications of the total accepted gap. The following section presents the model developed to describe the freeway vehicle's behavior at the ramp merge areas, along with a discussion on the data used to develop this model. The macroscopic model that quantifies the observed turbulence due to the merging maneuvers and associates this turbulence with the breakdown probability is discussed in the next section. This chapter concludes with a discussion of the developed models.

Development of the Gap Acceptance Model

Estimation Dataset for Gap Acceptance Model

The estimated parameters used for the merging gap acceptance model are presented in this section. Descriptive statistics of the estimated parameters are given for the entire dataset and also as a function of the merging maneuver type (free, cooperative, or forced) and the driver behavior type (aggressive, average and conservative).

Out of the 273 total observations of merging maneuvers, several free merges did not involve any freeway lag or lead vehicle therefore these were removed from the dataset. Also, the cooperative maneuvers that resulted in the lag vehicle changing lanes were excluded since these do not provide information about the gap acceptance behavior of the ramp vehicle (i.e., the final selected gaps were free gaps). Lastly, merging maneuvers that occurred under complete congested conditions were not considered as well since gap acceptance under those conditions is

different. The final estimation dataset includes 142 merging observations across the five freeway-ramp junctions.

An illustration of the gaps related to the ramp vehicle and the lead and lag vehicles is provided in Figure 6-1. This figure also shows the positions of the three vehicles with respect to the white solid line and the entire length of the acceleration lane (parallel type), measured from the gore.

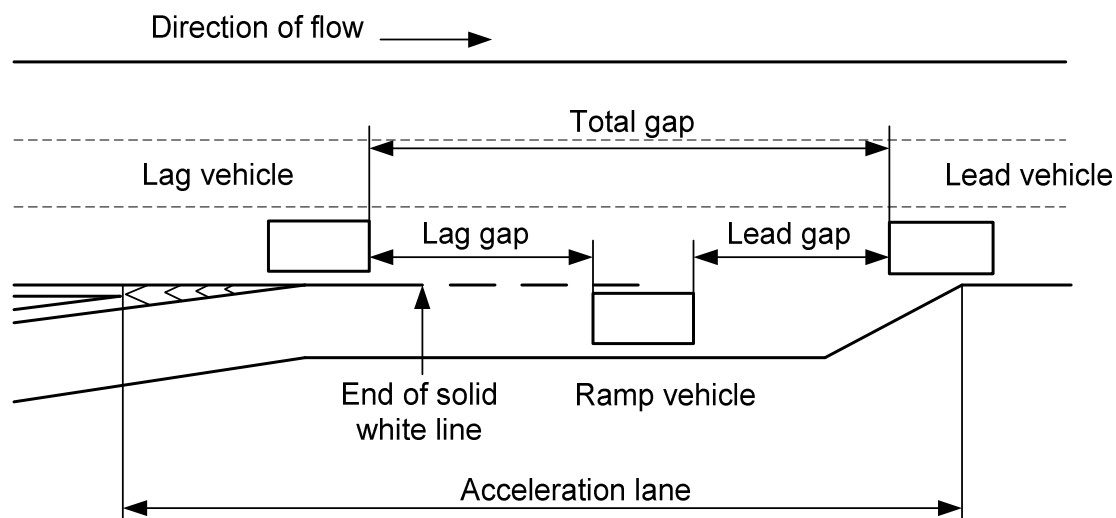


Figure 6-1. The ramp, lag and lead vehicle, their related gaps and positions.

The ramp vehicle merging speed ranged from 34.0 to 65.7 mi/h with an average of 55.1 mi/h, and its acceleration ranged from 0.0 to 5.9 ft/s² with an average acceleration of 1.1 ft/s². The relative speeds with respect to the lag and lead vehicles were calculated as the speeds of these vehicles less the speed of the ramp merging vehicle. The average relative speed with the lag vehicle was found to be -0.2 mi/h, varying from -11.2 mi/h to 18.3 mi/h. The average relative speed with the lead vehicle was 2.6 mi/h, varying from -4.5 mi/h to 16.8 mi/h. Histogram of the ramp vehicle speed is presented in Figure 6-2.

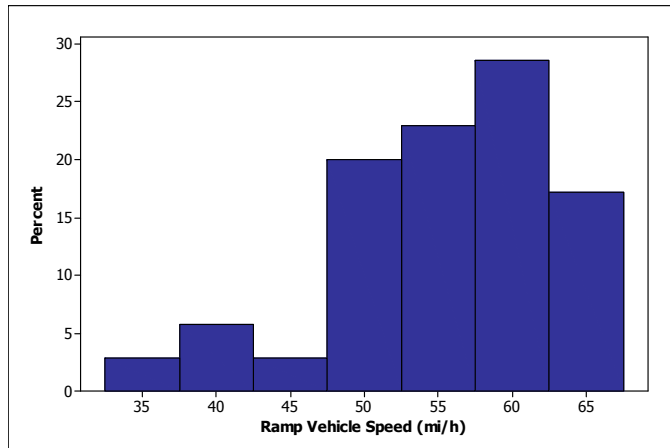
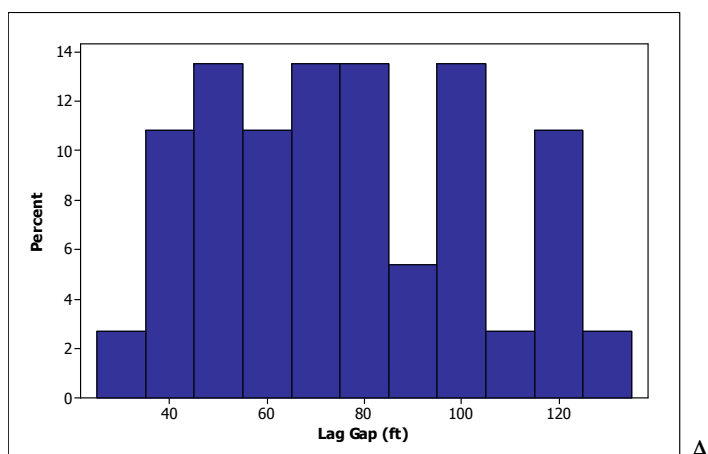


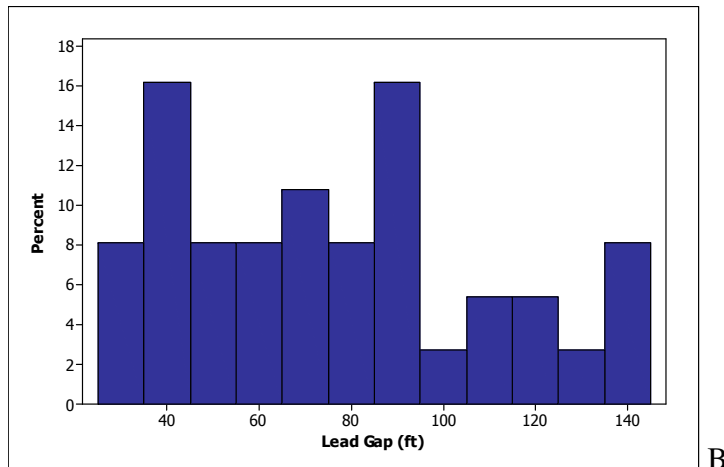
Figure 6-2. Distribution of ramp vehicle speed.

Traffic conditions such as the average density and the speed in the right-most lane affect the gap acceptance behavior of the ramp vehicle. The per-lane average density during the merging maneuvers was 30.8 veh/h/ln and it ranged from 10.9 to 52.8 veh/h/ln. The mean freeway speed of the right-most lane was 59.1 mi/h, ranging from 43.0 mi/h to 71.0 mi/h. The gaps with the lag vehicle range from 34.9 ft to 134.8 ft with an average of 75.5 ft. The gaps with the lead vehicle range from 25.2 ft to 140.1 ft, with an average gap of 74.8 ft. Lastly, the total gaps (measured when both lead and lag gaps were available) range from 84.3 ft to 222.9 ft, with an average total gap of 150.3 ft. The distribution of the gaps is shown in Figure 6-3.

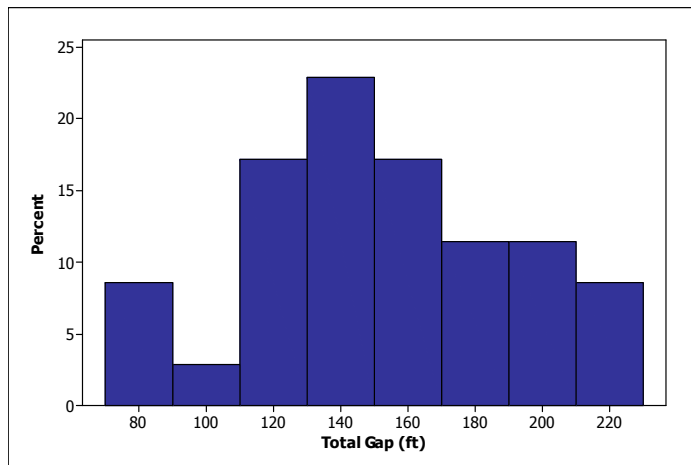


A

Figure 6-3. Distributions of A) lag gap, B) lead gap, and C) total gap.



B



C

Figure 6-3. Continued.

The analysis results of the merging position and acceleration lane usage by ramp design is shown Table 6-1. It was found that, compared to parallel type on-ramps drivers used more length on the tapered on-ramps before merging. On parallel on-ramps the acceleration lane usage averaged to 40.1 percent, however, there were few observations where the participants made almost full use of the lane (maximum usage was 83.3 percent). Also, there were few merging maneuvers on parallel on-ramps that were completed prior to the end of the solid white line (minimum position denoted as -50 ft on Table 6-1).

Table 6-1. Statistics of merging position by ramp design

Parameter	Ramp design	Mean	St.dev.	Minimum	Median	Maximum
Position rel. to solid white line (ft)	Parallel	127.6	116.6	-50.0	99.8	480.0
	Taper	132.5	72.6	28.5	137.1	246.9
Acceleration lane used (%)	Parallel	40.1%	12.5%	23.9%	37.6%	83.3%
	Taper	65.8%	6.0%	57.3%	66.2%	75.2%

On average, the merging position considering both types of ramp design was found to be 129.0 ft downstream of the end of the solid white line, and the acceleration lane usage measured from the gore area to the end of the lane (Figure 6-1) averaged to 48.2 percent.

The parameters related to the ramp vehicle were also grouped based on driver behavior and merging maneuver type. Table 6-2 presents the ramp vehicle speeds, accelerations, gaps, and merging positions associated with the free merging maneuvers. The average density under free merging was 26.6 veh/h/ln and the average speed on the right-most lane was 60.4 mi/h.

Table 6-2. Statistics of ramp vehicle gap acceptance parameters by driver type for free merges

Parameter	Driver type	Mean	St.dev.	Minimum	Median	Maximum
Ramp vehicle speed (mi/h)	Aggressive	58.2	5.6	52.0	58.0	65.7
	Average	61.8	2.6	59.0	62.0	64.0
	Conservative	48.5	9.2	42.0	48.5	55.0
Ramp vehicle acceleration (ft/s ²)	Aggressive	1.4	1.9	0.0	0.0	4.9
	Average	0.4	0.7	0.0	0.0	1.5
	Conservative	0.0	0.0	0.0	0.0	0.0
Lag vehicle gap (ft)	Aggressive	92.9	26.1	49.1	95.5	134.8
	Average	66.0	22.0	47.9	59.6	97.0
	Conservative	95.1	34.6	70.7	95.1	119.6
Lead vehicle gap (ft)	Aggressive	75.0	32.9	25.2	66.6	140.1
	Average	102.5	32.0	72.6	98.6	139.9
	Conservative	70.7	17.5	58.4	70.7	83.1
Total gap (ft)	Aggressive	168.0	41.5	91.6	178.6	222.9
	Average	168.5	25.1	132.7	176.7	187.8
	Conservative	165.9	17.2	153.7	165.9	178.0
Position rel. to solid white line (ft)	Aggressive	119.8	64.7	28.5	104.5	246.9
	Average	139.9	53.1	66.3	153.5	186.0
	Conservative	163.0	279.0	-34.0	163.0	360.0
Acceleration lane used (%)	Aggressive	51.0%	16.0%	30.6%	46.3%	75.2%
	Average	59.2%	18.5%	31.5%	67.5%	70.2%
	Conservative	37.8%	18.2%	24.9%	37.8%	50.7%

Table 6-2 shows that the average speeds and accelerations of the merging vehicle under free merging do not vary significantly by driver type. Also, with respect to the accepted gaps, the data do not reveal any trend based on driver type. This is expected since in free merges the gap selection should be random and independent of drivers' interactions. Regarding the merging position the data show that drivers make use of at most 59.2 percent of the acceleration lane, which possibly indicates that they have reached an acceptable speed and acceleration for merging freely.

The summary statistics of the ramp vehicle-related parameters in cooperative merging maneuvers are presented in Table 6-3. The average density under this type of merging maneuvers was 32.4 veh/h/ln and the average speed on the right-most lane was 56.2 mi/h.

Table 6-3. Statistics of ramp vehicle gap acceptance parameters by driver type for cooperative merges

Parameter	Driver type	Mean	St.dev.	Minimum	Median	Maximum
Ramp vehicle speed (mi/h)	Aggressive	48.8	12.0	34.0	50.2	61.0
	Average	53.3	5.9	49.0	51.0	60.0
	Conservative	49.0	8.5	41.0	47.0	53.0
Ramp vehicle acceleration (ft/s ²)	Aggressive	1.8	2.1	0.0	1.5	4.2
	Average	0.2	0.3	0.0	0.0	0.5
	Conservative	0.0	0.0	0.0	0.0	0.0
Lag vehicle gap (ft)	Aggressive	47.6	17.1	34.9	41.6	72.5
	Average	68.4	27.4	44.6	62.4	98.3
	Conservative	83.8	30.4	62.3	83.8	105.4
Lead vehicle gap (ft)	Aggressive	67.1	36.6	39.1	56.4	116.6
	Average	92.1	47.8	43.1	94.7	138.6
	Conservative	66.8	17.9	54.1	66.8	79.5
Total gap (ft)	Aggressive	114.7	27.5	84.6	111.5	151.4
	Average	160.5	35.1	139.2	141.4	201.0
	Conservative	150.7	12.5	141.8	150.7	159.5
Position rel. to solid white line (ft)	Aggressive	204.1	188.8	75.0	130.6	480.0
	Average	176.7	76.2	95.0	189.3	245.9
	Conservative	73.4	50.3	37.8	73.4	109.0
Acceleration lane used (%)	Aggressive	48.2%	23.5%	33.0%	38.3%	83.3%
	Average	43.5%	12.6%	33.3%	39.5%	57.6%
	Conservative	46.7%	24.2%	29.6%	46.7%	63.9%

Table 6-3 shows the variation of average speed and acceleration by driver type. Aggressive drivers appear to have the lowest average merging speeds, however, the observed variability in their speeds was high (12 mi/h). The data also show a distinct trend of the accepted gaps by driver type. Gaps (primarily the lag and total) decrease as the degree of aggressiveness increases. Also, with respect to the merging position, vehicles make use of less than 50 percent of the acceleration lane when accepting a gap after the freeway vehicle's cooperation.

The summary statistics of the ramp vehicle-related parameters in forced merging maneuvers is presented in Table 6-4. The average density for the observed forced merges was 36.5 veh/h/ln, and the average speed on the right-most lane was 59.1 mi/h.

Table 6-4. Statistics of ramp vehicle gap acceptance parameters by driver type for forced merges

Parameter	Driver Type	Mean	St.Dev.	Minimum	Median	Maximum
Ramp vehicle speed (mi/h)	Aggressive	56.1	4.9	49.0	57.8	60.0
	Average	52.0	2.0	50.0	52.0	54.0
Ramp vehicle acceleration (ft/s ²)	Aggressive	2.8	1.8	1.0	1.7	5.9
	Average	2.0	0.8	1.5	1.5	2.9
Lag vehicle gap (ft)	Aggressive	55.7	18.9	37.2	52.3	81.3
	Average	64.4	21.0	41.5	68.7	82.9
Lead vehicle gap (ft)	Aggressive	49.9	29.6	31.9	36.8	94.1
	Average	71.0	34.4	31.4	87.8	93.8
Total gap (ft)	Aggressive	105.6	22.5	84.3	103.4	131.3
	Average	135.4	21.1	114.4	135.3	156.6
Position rel. to solid white line (ft)	Aggressive	46.2	91.3	-50.0	32.5	170.0
	Average	133.0	91.2	29.1	170.0	200.0
Acceleration lane used (%)	Aggressive	39.0%	13.8%	23.9%	37.4%	57.3%
	Average	45.7%	8.6%	35.9%	48.9%	52.2%

None of the conservative drivers was observed to perform a forced merge, and this is expected considering the characteristics of this driver type, as it was also discussed in Chapter 5.

The findings indicate that aggressive drivers merge with higher speeds than average drivers. Also, the speeds and accelerations of both types of drivers are higher than those recorded under cooperative merging (Table 6-3). Aggressive drivers also accept smaller gaps than average

drivers (lead, lag and total). Lastly, both aggressive and average drivers have initiated the merge after covering 39.0 and 45.7 percent of the acceleration lane, respectively.

The Gap Acceptance Model

The gap acceptance model is based on field observations of the total accepted gaps (Figure 6-1). For the model development, the total accepted gaps were assumed to follow a lognormal distribution to ensure their non-negativity. Regression was performed considering all types of merging maneuvers. The general form of the total gap is:

$$\ln(\text{Gap}) = \alpha + \beta^T X \quad (6.1)$$

Or, equivalently,

$$\text{Gap} = \exp(\alpha + \beta^T X) \quad (6.2)$$

Where, α is a constant, X is vector of explanatory variables affecting the total gap under the different types of merging maneuvers, β^T is the corresponding vector of parameters.

As it was shown in Table 6-2 through Table 6-4, the accepted gaps vary as a function of the driver type. Although drivers were categorized to three driver types (aggressive, average and conservative), only two types were eventually used in the regression model, namely, the aggressive and the non-aggressive drivers (i.e., average and conservative drivers). This was primarily because the differences between the average and the conservative drivers were minimal.

The total gap is a function of the maneuver type (free, cooperative or forced), the proportion of the acceleration lane used by the ramp vehicle and its acceleration, the average per-lane density, and whether the ramp driver is aggressive. The results of the regression model for the total accepted gaps when merging is shown in Table 6-5.

Table 6-5. Parameter estimates for total accepted gap

Parameter	Parameter value	t-statistic
Constant	5.343	33.46
Free Merge	0.141	1.86
Aggressive driver*forced merge	-0.324	-2.80
Aggressive driver*cooperative merge	-0.262	-2.46
Proportion acceleration lane used	-0.445	-2.43
Average density (veh/mi/ln)	-0.005	-1.66
Ramp vehicle acceleration (ft/s ²)	0.032	1.84

All selected explanatory variables are significant at the 90% confidence level. The R^2 of Equation 6.3 is 65.5 percent which indicates the percent of variance in the average total gaps explained by the selected explanatory variables.

As expected, gaps under free merging are larger than under cooperative or forced merging. Also, the model does not distinguish differences between the driver types in gap acceptance decisions under free merges.

However, gap acceptance under cooperative or forced merging does depend on the driver type. The model suggests that aggressive drivers merge at smaller gaps than non-aggressive drivers, when performing cooperative or forced merging maneuvers. Also, the gaps under forced merging are smaller than under cooperative merging for aggressive drivers. For non-aggressive drivers, the differences in gap acceptance between forced and cooperative merging maneuvers were not significant. Therefore, the model captures differences in gap acceptance between free and constrained (cooperative or forced) merging maneuvers.

The model suggests that the total accepted gap decreases as the vehicle is approaching the end of the acceleration lane. This trend indicates that the urgency to merge increases for all drivers as they approach the end of the lane, and they are willing to accept smaller gaps. The trend between the total gap and the proportion of acceleration lane used, by driver type and

merging maneuver, is shown in Figure 6-4. Average values of density and ramp vehicle acceleration were assumed for this graph.

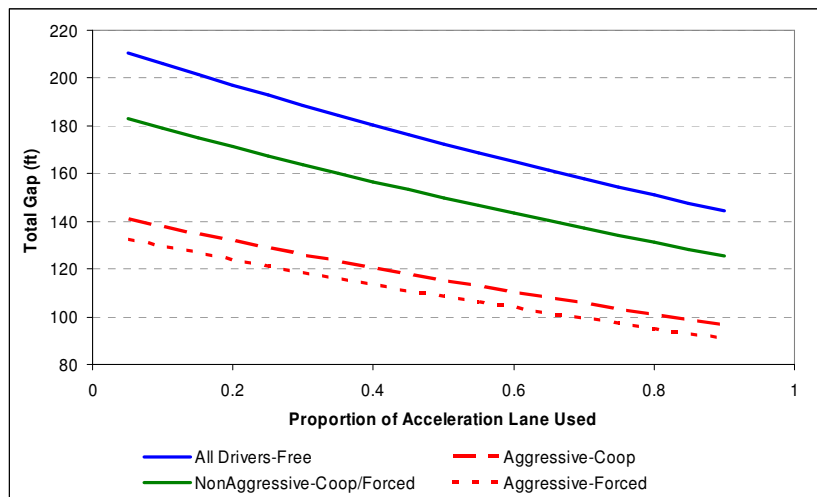


Figure 6-4. Relationship between total gap and proportion of acceleration lane used by driver type and maneuver type.

The total gaps increase with increase in the ramp vehicles' acceleration, indicating that the ramp vehicle has accelerated closer to the freeway speed. The relationship between the vehicle's acceleration depending on their behavior as well as the maneuver type is shown in Figure 6-5.

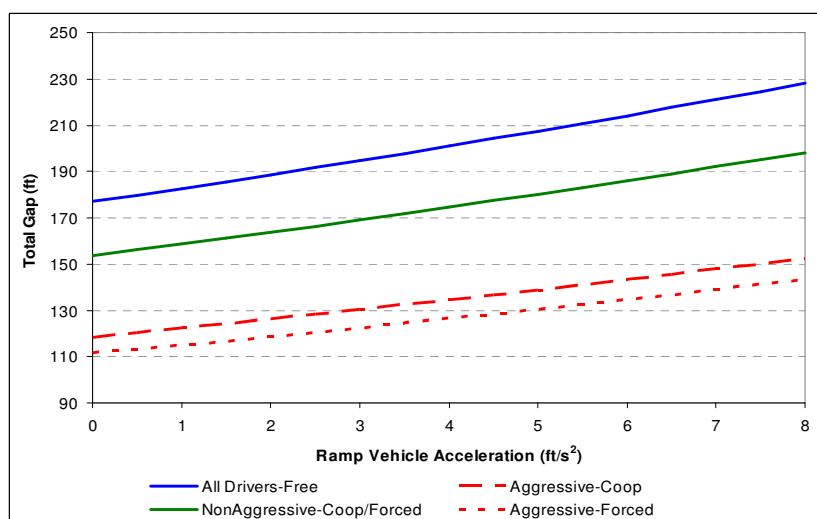


Figure 6-5. Relationship between total gap and ramp vehicle's acceleration by driver type and maneuver type.

The model suggests that the total gap decreases when the average density increases. This is because in dense traffic conditions smaller gaps are available for all drivers to accept. Figure 6-6 shows the relationship between the average density and the total gap depending on the maneuver type and driver's aggressiveness. Average values for the proportion of acceleration lane used and the ramp vehicle's acceleration were applied to develop this relationship.

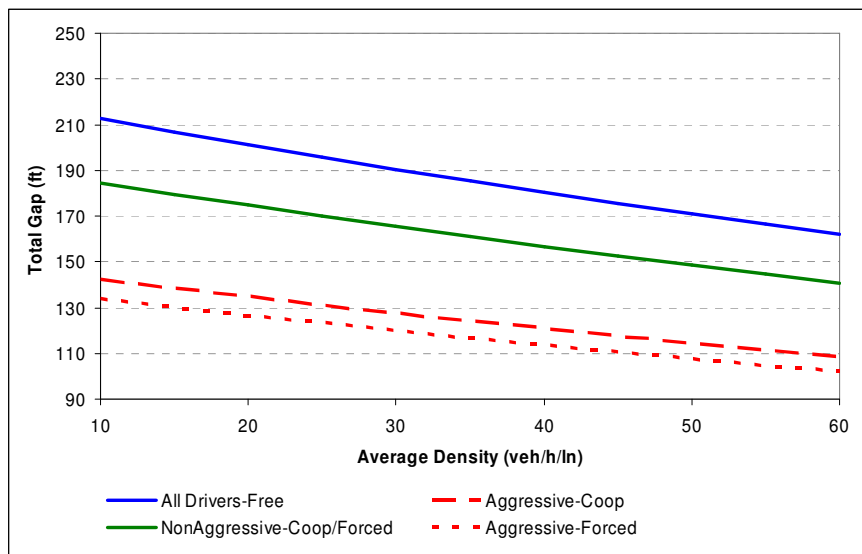


Figure 6-6. Relationship between total gap and average density by driver type and maneuver type.

Development of the Deceleration Model

The probability that any freeway vehicle decelerates when facing a cooperative or forced merging situation is captured by the deceleration probability model. This model has two components. The first component describes the event that a freeway vehicle will decelerate by providing cooperation, indicating the transition from the normal state (no interaction) to the cooperative state. The second component captures the event that a freeway vehicle will decelerate as a response to a forced merge by the ramp vehicle, given that no cooperation was provided earlier. This assumes the transition of the freeway vehicle from the normal state (no interaction) to the forced state. These two events are mutually exclusive, i.e., they cannot occur

simultaneously. Therefore, the deceleration probability model can be described by the following expression:

$$P_n(DEC_t) = P_n(DEC, s_{n,t} = \text{coop}/s_{t-1,n} = \text{normal}) + P_n(DEC, s_{n,t} = \text{forced}/s_{t-1,n} = \text{normal}) \quad (6.3)$$

Where $s_{t,n}$ is the state of the freeway vehicle n at time t , which can be normal (no interaction), cooperative, or forced.

This section describes the dataset and presents the model formulation for both components.

Estimation Dataset for Deceleration Model

This section describes the datasets used to develop the initiation of cooperation model and the forced merging model.

Dataset for initiation of cooperation

Observations of the participants while they were driving on the freeway passing through a merge junction were used to model their reactions (deceleration, lane changing or do nothing) towards the merging ramp vehicles. The estimation dataset for this model includes observations both before, and at the time the participant starts to yield to the ramp vehicle. Typically, participants' actions would be observed as soon as they could see the (potentially interacting) ramp vehicle entering the acceleration lane, and until they had expressed their decision to decelerate, change lanes, or driver uninterrupted, by clearly stating so.

The sample includes twenty-three observations where the freeway vehicle cooperated by either decelerating or changing lanes (Table 5.2), and thirty-one observations where no cooperation was provided. 13 percent of these observations were decelerations, 29.6 percent were lane changes and for the remaining 57.4 percent the drivers did not cooperate.

The ramp vehicle speed ranged from 38 to 67.4 mi/h with an average of 54.4 mi/h, and the freeway vehicle speed ranged from 52 mi/h to 75 mi/h, with an average speed of 64 mi/h. The relative speed between the freeway vehicle and the ramp vehicle is calculated as the speed of the

freeway vehicle less the speed of the ramp vehicle. Histograms of the relative speed and the freeway vehicle are presented in Figure 6-7.

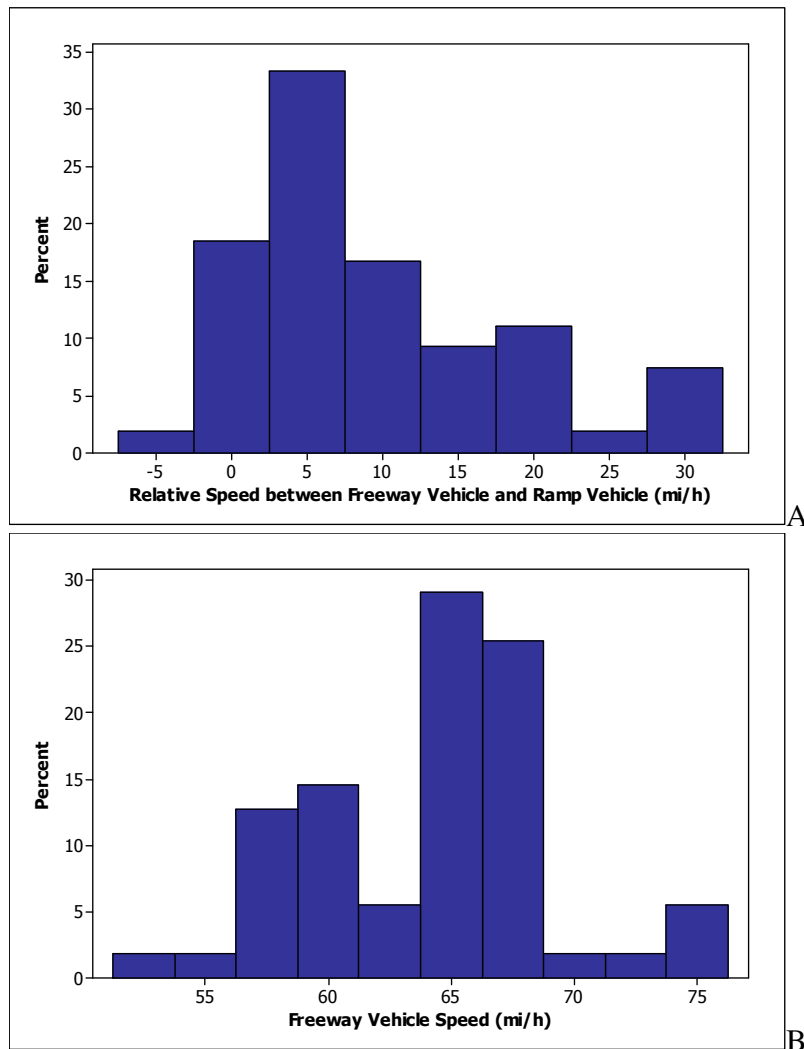


Figure 6-7. Distribution of A) relative speed between the freeway vehicle and the ramp vehicle, and B) freeway vehicle speed for initiation of cooperation.

The average freeway density was 22.1 veh/mi/ln, and it covers a wide range of values, from 6.6 veh/mi/ln to 40 veh/mi/ln. The average freeway speed on the right lane was 63.2 mi/h ranging from 46 to 70 mi/h. Histograms of the density and the speed difference between the freeway vehicle and the average speed on the right lane (right lane average speed less the speed of the subject-freeway vehicle) are shown in Figure 6-8.

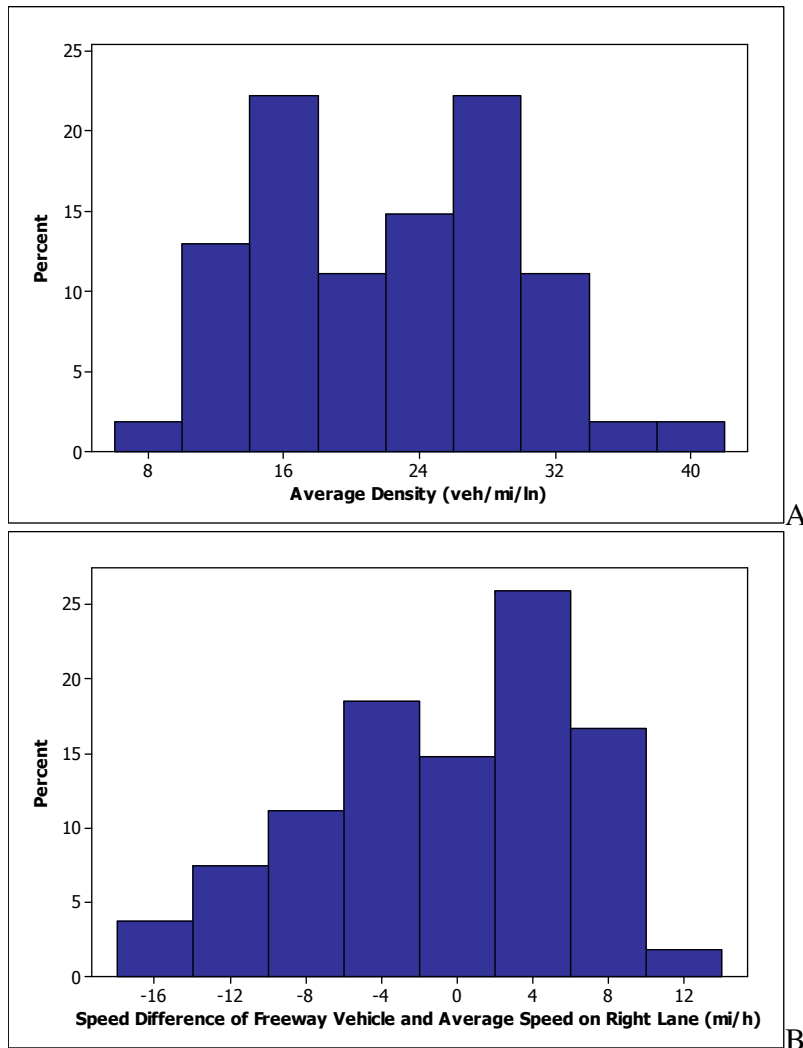


Figure 6-8. Distribution of A) average density, and B) speed difference between the freeway vehicle and the average speed on the right lane for initiation of cooperation.

The speed difference histogram in Figure 6-8 shows the speed difference covers a wide range suggesting that in many cases the participants were driving on greater or less speed than their lane average.

The average distance between the ramp vehicle and the freeway vehicle before initiating a cooperative maneuver was found to be 118 ft, ranging from 39.5 ft to 257 ft. Also, the average position of the ramp vehicle, in terms of proportion of acceleration lane used was 0.21 (ranging from -0.03 to 0.65). The negative sign of the minimum proportion suggests that the freeway

vehicle reacted before even the ramp vehicle entered the acceleration lane. The mean ramp vehicles' position as a function of the remaining distance to the end of the acceleration lane is 821 ft, and its range is from 211.4 ft to 1675 ft. The average distance between the freeway (subject) vehicle and the ramp vehicle is 118.7 ft ranging from 39.5 ft to 257 ft.

Dataset for initiation of forced merging

The dataset for the forced merging model contains twenty-four observations of forced merging maneuvers performed by the participants. A forced merge was assumed to be initiated as soon as the ramp vehicle starts to cross the line.

The dataset for this model includes the data used for the gap acceptance under forced merging conditions (Table 6-4). Additional data obtained before the initiation of the forced maneuver, as well as data where the ramp vehicle did not initiate a forced merge and the freeway vehicle did not show any cooperation were also used. Summary statistics of the data used for the development of the forced merging model are shown in Table 6-6.

Table 6-6. Statistics of dataset for forced merging model

Parameter	Average	St.dev.	Minimum	Median	Maximum
Ramp vehicle speed (mi/h)	56.00 (50.79)	4.38 (8.41)	49.00 (24.00)	57.50 (51.00)	61.00 (62.50)
Ramp vehicle acceleration (ft/s ²)	2.57 (0.63)	2.18 (1.05)	0.00 (0.00)	2.20 (0.00)	7.33 (4.40)
Lag vehicle relative speed (mi/h)	1.46 (6.72)	4.84 (6.82)	-3.27 (-4.61)	0.50 (5.74)	14.41 (27.36)
Average right-lane speed (mi/h)	58.67 (58.42)	6.33 (6.75)	50.00 (37.00)	57.50 (58.00)	68.00 (76.00)
Cluster size	1.67 (1.82)	0.78 (0.89)	1.00 (1.00)	1.50 (2.00)	3.00 (4.00)
Average density (veh/mi/ln)	36.45 (30.12)	12.16 (10.72)	18.21 (12.35)	37.09 (30.80)	52.80 (52.80)
Proportion acceleration lane used	46.8% (23.0%)	13.3% (14.0%)	23.9% (5.0%)	46.6% (25.1%)	75.5% (49.4%)

Data in parenthesis are for the entire dataset.

Deceleration Model Due to Cooperative Merging

The freeway through vehicle is facing three choices when identifying a ramp vehicle which is subject to merge. The freeway vehicle may decide to either provide cooperation to the ramp vehicle by decelerating or by changing lanes, or to continue driving uninterrupted.

Based on the focus group discussions and the field observations the decision-making process was modeled as a Multinomial Logit (MNL) Model, where the freeway vehicle has three choices: to decelerate, to change lanes, to do nothing. If gaps are not available, then lane changing is not an option, thus the freeway vehicles' choices are to decelerate or not yield to the ramp vehicle.

The utilities of the choices for the freeway vehicle n are:

$$U_{i,n} = V_{i,n} + \varepsilon_{i,n} \quad (6.4)$$

$i = \text{decelerate, change lanes, no-coop initiation}$

Where, $V_{i,n}$ are the deterministic components of the utilities of driver n to decelerate, change lanes and to not initiate cooperation. For the estimation of the deterministic components of the utilities the reference choice was the choice to decelerate. The utilities for the remaining choices are:

$$V_{i,n} = X_{i,n} \cdot \beta_{i,n} \quad (6.5)$$

$i = \text{decelerate, change lanes, no-coop initiation}$

Where $X_{i,n}$, are the vectors of explanatory variables that affect the utilities to change lane, decelerate and do nothing. $\beta_{i,n}$ are the corresponding vectors of the parameters. The vectors of explanatory variables include only generic variables. The final model parameters of the MNL model are presented in Table 6-7. The log-likelihood function for this model is -39.499 and the adjusted rho-square is 0.216.

Table 6-7. Parameter estimates for MNL model.

Explanatory variables	No cooperation		Change lanes	
	Parameter	t-statistic	Parameter	t-statistic
Constant	2.055	1.574	4.179	3.509
Distance to end of acceleration lane	0.002	2.107	0.002	2.107
Cluster size	-0.724	-1.710	-	-
Min ($0, V_{avg} - V_n$) (non conservative drivers)	-0.144	-1.600	-	-
Distance to ramp vehicle (conservative drivers)	0.008	1.188	-	-
Distance to ramp vehicle (all drivers)	-	-	-0.018	-2.337
Average density (veh/mi/ln)	-	-	-0.071	-1.623

Both utilities of do nothing and change lanes depend on the position of the ramp vehicle with respect to the end of the acceleration lane. Although the proportion of acceleration lane used is a parameter more suitable to the data (due to observations at ramp junctions with different geometry), the remaining distance was found to be more significant, probably because the freeway vehicle is more sensitive to the distance left, irrespective of the how far on the acceleration lane the ramp vehicle has traveled. As the ramp vehicle approaches the end of the lane (distance decreases), the utilities of change lanes or do nothing decrease, and therefore, the probability of decelerating increases. Figure 6-9 shows the probabilities of deceleration, lane changing and no cooperation as a function of the remaining distance and driver type (conservative and non-conservative). Average conditions were assumed for the development of this graph.

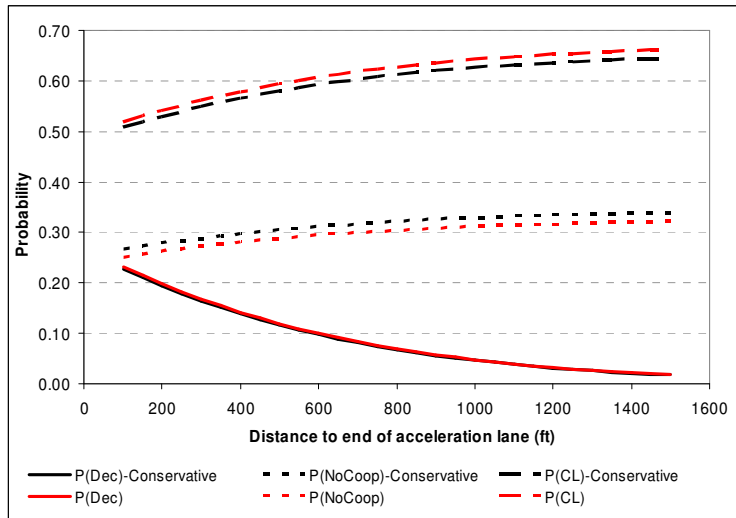


Figure 6-9. Probability of decelerating, changing lanes or no cooperating as a function of the distance to end of the acceleration lane for conservative and non-conservative drivers.

According to Figure 6-9, the probability of deceleration is not sensitive to driver types, however non-conservative drivers are more likely to change lanes than conservative drivers.

The decision of the freeway vehicle also depends on the number of ramp vehicles present (cluster size). Increased number increases the probability that the ramp vehicle will cooperate (Figure 6-10).

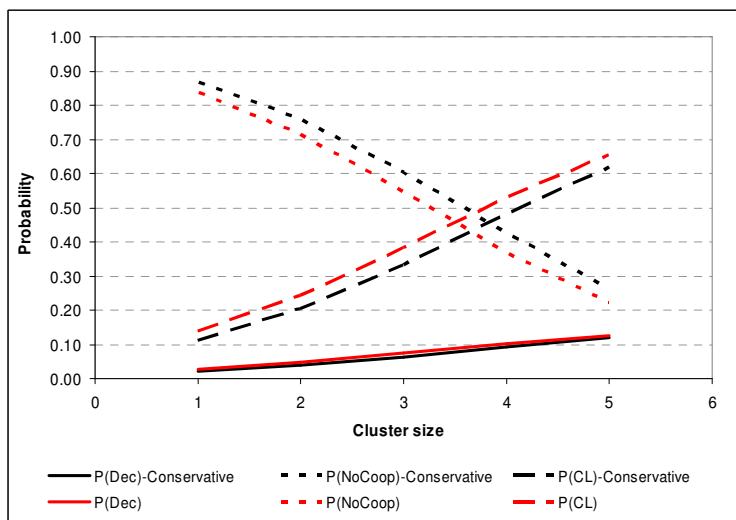


Figure 6-10. Probability of decelerating, changing lanes or no cooperating as a function of the cluster size for conservative and non-conservative drivers.

When the number of vehicles on the ramp is small, drivers are less likely to show any cooperation. Figure 6-10 also shows that conservative drivers are less likely to change lanes, however, the probability of decelerating is almost the same for all drivers.

As the distance between the ramp vehicle decreases, all drivers are more likely to change lanes, and less likely to decelerate. Figure 6-11 shows the effect of the distance to the ramp vehicle on the freeway vehicle decisions by driver type.

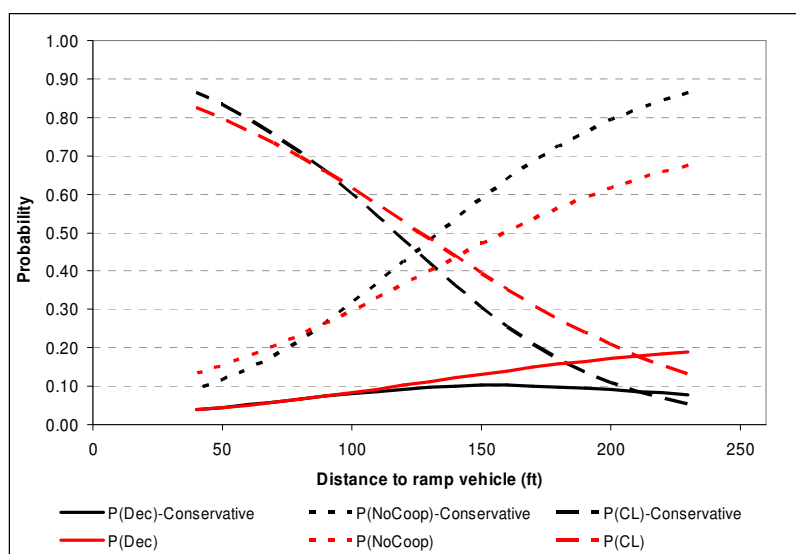


Figure 6-11. Probability of decelerating, changing lanes or no cooperating as a function of distance to the ramp vehicle for conservative and non-conservative drivers.

Figure 6-11 also shows that when the distance between the two vehicles is large, conservative drivers are more likely not to provide cooperation, whereas non-conservative drivers have increased probability of initiating cooperation compared to conservative drivers. Also, as the distance decreases, conservative drivers will become more aware and they are more willing to change lanes.

The average density also affects the utility of changing lanes. Increase of the average density reduces the probability of changing lanes and increases the probability of decelerating as well as showing no cooperation. Also, increase of the negative relative speed between the

freeway vehicle and lane average speed increases the probability of decelerating or changing lanes. This parameter concerns the non-aggressive drivers, and it suggests that when the freeway vehicle speed is close to the average speed, the vehicle is more likely to cooperate.

The probability that any freeway vehicle n will select to decelerate is given in Equation 6.6:

$$P_n(DEC, s_{t,n} = coop / s_{t-1,n} = normal) = \frac{\exp(V_{DEC,n})}{\exp(V_{DEC,n}) + \exp(V_{CL,n}) + \exp(V_{NO-Coop,n})} \quad (6.6)$$

Deceleration Model Due to Forced Merging

In the dataset, all observations of forced merging lead to decelerations of the freeway vehicles. Therefore, the deceleration model is equivalent to modeling the probability that any ramp vehicle r will initiate a forced merge.

$$P_n(DEC, s_{t,n} = forced / s_{t-1,n} = normal) = P_r(s_{t,r} = forced / s_{t-1,r} = normal) \quad (6.7)$$

The ramp vehicle will initiate a forced merge given that the freeway lag vehicle has not shown any cooperation earlier (previous state is normal). This model can be expressed as a binary choice model where the two choices of the ramp vehicle, are to initiate a forced merge or not. The utilities of the two alternatives are:

$$V_{j,r} = X_{j,r} \cdot \beta_{j,r} \quad (6.8)$$

$j = \text{initiate forced, do not initiate forced}$

The parameter estimates for the utility to initiate a forced merge with the respective t-statistics are presented in Table 6-8. The log-likelihood function for this model is -11.060 and the adjusted rho-square is 0.619. All parameters are statistically significant at a 90% confidence level.

Table 6-8. Parameter estimates for utility of initiation forced merge

Explanatory variables	Initiate forced merge	
	Parameter value	t-statistic
Constant	-15.28	-2.76
Average density (veh/mi/ln)	0.10	1.93
Proportion of acceleration lane used	21.64	2.71
Number of ramp vehicles on ramp (aggressive ramp driver)	1.14	1.61
Ramp acceleration (ft/s ²)	0.88	1.64

Based on this model, the probability of initiating a forced merge and therefore the probability that the freeway vehicle will decelerate is:

$$P_n(DEC, s_{t,n} = forced / s_{t-1,n} = normal) = \frac{1}{1 + \exp(-V_{Forced,r})} \quad (6.9)$$

As it was also concluded from the focus group experiment, aggressive drivers are more likely to initiate a forced merge than average drivers. Conservative drivers did not show any indication of initiating a forced merge. This was also confirmed from the instrumented vehicle experiment, since none of the conservative drivers performed a forced merging maneuver. Ramp drivers' aggressiveness is captured through a dummy variable related to the number of ramp vehicles ahead of the subject ramp vehicle. Aggressive ramp drivers become more eager to enter the freeway if there are other vehicles in front of them waiting to merge. Due to their aggressive nature, they might seek a gap and merge sooner, causing the freeway vehicles to decelerate.

Increase in average density also reduces the availability of gaps, therefore ramp vehicles are more willing to force their way into the freeway. Assuming average conditions, the relationship between traffic density and the forced merging probability considering drivers' aggressiveness is shown in Figure 6-12.

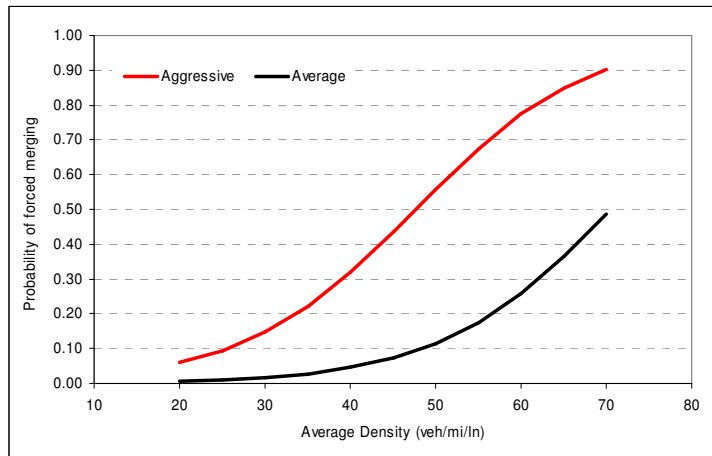


Figure 6-12. Forced merging probability as a function of average density and driver's aggressiveness.

In addition, the probability of initiating a forced merge increases as the ramp vehicle travels on the acceleration lane. Figure 6-13 shows the relationship between the forced merge probability and the proportion of acceleration lane used by the ramp driver as a function of its aggressiveness.

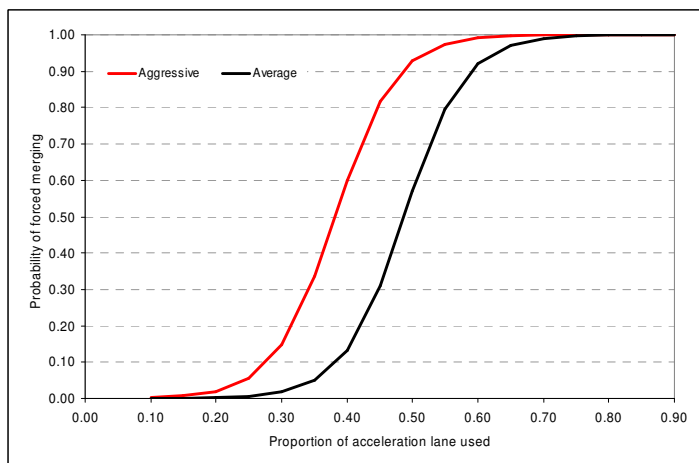


Figure 6-13. Forced merging probability as a function of proportion of acceleration lane used and driver's aggressiveness.

Increased acceleration also suggests increase in the probability of performing a forced merge. This is probably because of the ramp vehicles' effort to increase rapidly their speed on the acceleration lane in order to decrease the speed difference with the lag vehicle and merge.

Figure 6-14 shows the relationship between ramp vehicle's acceleration and the probability of initiating a forced merge. As expected, aggressive drivers are more likely to perform a forced merge than average drivers.

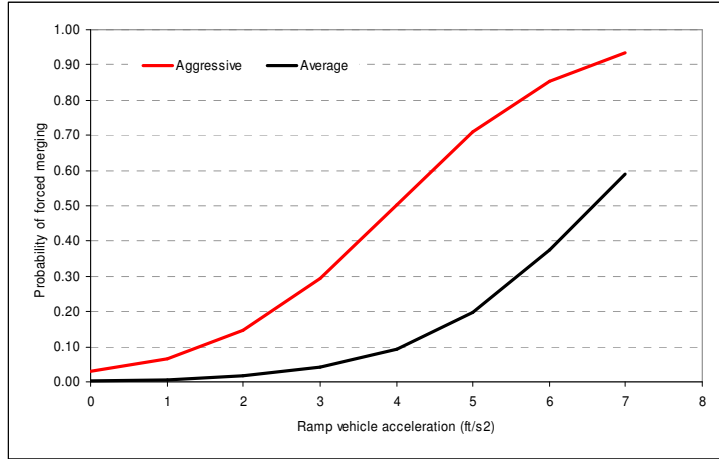


Figure 6-14. Forced merging probability as a function of the ramp vehicle acceleration and driver's aggressiveness.

The Deceleration Probability Model

Considering the equations 6.3, 6.6, and 6.9, the model that describes the probability that the freeway vehicle will decelerate at the merge area is summarized in the following equation:

$$P_n(DEC_t) = \frac{\exp(V_{DEC,n})}{\exp(V_{DEC,n}) + \exp(V_{CL,n}) + \exp(V_{NO-Coop,n})} + \frac{1}{1 + \exp(-V_{Forced,r})} \quad (6.10)$$

The Merging Turbulence Model

The merging turbulence model transfers the deceleration probability model to the macroscopic level. The merging turbulence model describes the probability (frequency) that N freeway vehicles will decelerate due to the merging ramp flow over time.

$$P(MergingTurbulence) = \frac{1}{RampFlowRate} \sum_{n=1}^N P_n(Dec) \quad (6.11)$$

The data for the merging turbulence model were obtained through video observations of two breakdown events at the J.T. Butler NB on-ramp. The first occurred during the morning peak

period and the second during the afternoon peak period. Vehicle decelerations due to merging, lane changing, and also due to other reasons not easily identifiable through the videos were recorded. The prevailing ramp and freeway flow was also obtained.

Typically, the decelerations became more frequent when the breakdown was imminent. A speed threshold criterion was applied for identifying the breakdown events, since this criterion is typically applied in capacity analysis studies. The breakdown events were identified when the average freeway speed at the merging area would drop below the 60 mi/h threshold (posted speed limit is 65 mi/h) for at least five minutes.

Time-series plots of speed were overlaid with the time-series of observed decelerations to compare the identified times to breakdown of the two methods. Figure 6-15 shows an example of the two time-series plots for one breakdown event.

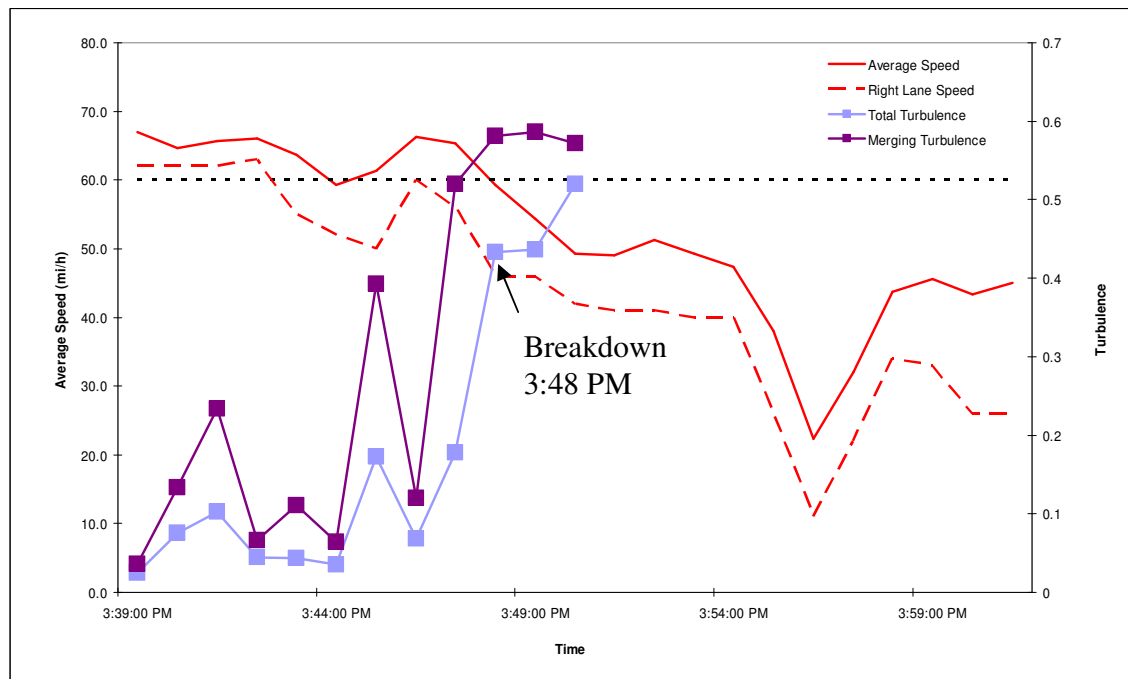


Figure 6-15. Time-series of speed and number of decelerations on October 9th, 2008.

Figure 6-15 shows an increasing trend of merging decelerations and total decelerations along with decrease in average speeds in all lanes. Based on the applied definition of breakdown, the breakdown is identified at 3:48 PM. Before the breakdown interval, the total decelerations include mostly decelerations due to merging and few decelerations due to lane changing. No decelerations are observed downstream of the merge. Two to three minutes before the breakdown (starting at 3:45) the merging turbulence increases abruptly. The total turbulence also increases slightly, indicating that most of the turbulence increase is due to merging decelerations. The number of lane changes also increases, however, these were not observed to cause any turbulence. The maximum merging turbulence observed before the breakdown exceeds 0.5, indicating that more than 50 percent of the merging maneuvers caused decelerations.

During the breakdown minute, the total turbulence increases even more, and exceeds 0.4. The proportion of vehicles decelerating due to merging remains high and over 0.5. Decelerations downstream of the merge start to appear. After that minute, the decelerations are more frequent, and some vehicles even stop at the middle and right lane for few seconds. The average speed has dropped at 50 mi/h and all incoming traffic is reducing speed to join the queues.

Figure 6-16 shows the relationship between the total freeway and ramp flow, and the merging turbulence probability for the same breakdown event. Generally, as the total flow increases, the merging turbulence probability increases as there are more opportunities for vehicle interactions. The highest merging turbulence observed one minute before the breakdown (3:47PM) exceeded 0.5. After the breakdown, the merging turbulence remains at high levels, however, the volume is decreasing. Several observations also resulted in zero merging turbulence probability and these observations. These were observed approximately twenty minutes earlier than the breakdown event.

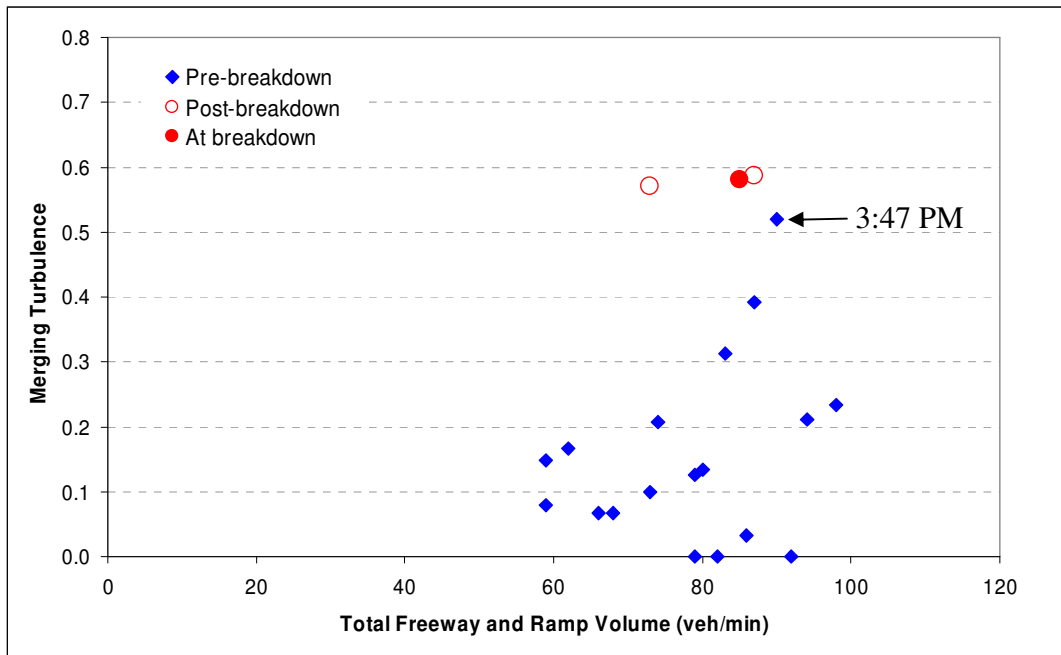


Figure 6-16. Relationship between total freeway and ramp flow and probability of merging turbulence.

Based on the field observations during the breakdown event it was found that there is a correlation between the merging turbulence and the speed reduction associated with the breakdown event. From Figure 6-15 it can be concluded that the total turbulence and the merging turbulence can serve as a precursor-indicator of the breakdown events, and could predict that the breakdown is imminent one to three minutes before the speed decrease is recorded on the detectors. Additional data are required to verify this conclusion.

The Breakdown Probability Model

This section discusses the proposed application of the merging turbulence model for developing the breakdown probability model. For the development of the breakdown probability model, field observations of merging maneuvers and the resulting merging turbulence frequency are required. A large sample size is also necessary (e.g., breakdowns over a six-month period). For the model development the breakdown intervals are identified considering the merging

turbulence criterion (e.g., when the turbulence exceeds 0.5). The Kaplan-Meier method could be used, as this was also applied in Brilon (2005).

According to the Kaplan-Meier method, the distribution function of the breakdown volume $F(q)$ is:

$$F(q) = 1 - \prod_{i: q_i \leq q} \frac{k_i - 1}{k_i}; i \in \{B\} \quad (6.12)$$

Where, q is the total freeway volume (veh/h), q_i is the total freeway volume (veh/h) during the breakdown interval i , (i.e., breakdown flow), k_i is the number of intervals with a total freeway volume of $q \geq q_i$ and $\{B\}$ is the set of breakdown intervals (1-minute observations).

An illustration of the breakdown probability model is shown in Figure 6-17. The curve was developed by applying the typical breakdown definition, where the speed drops below the 60-mi/h threshold. The breakdown observations were during the am peak period and cover six months of data.

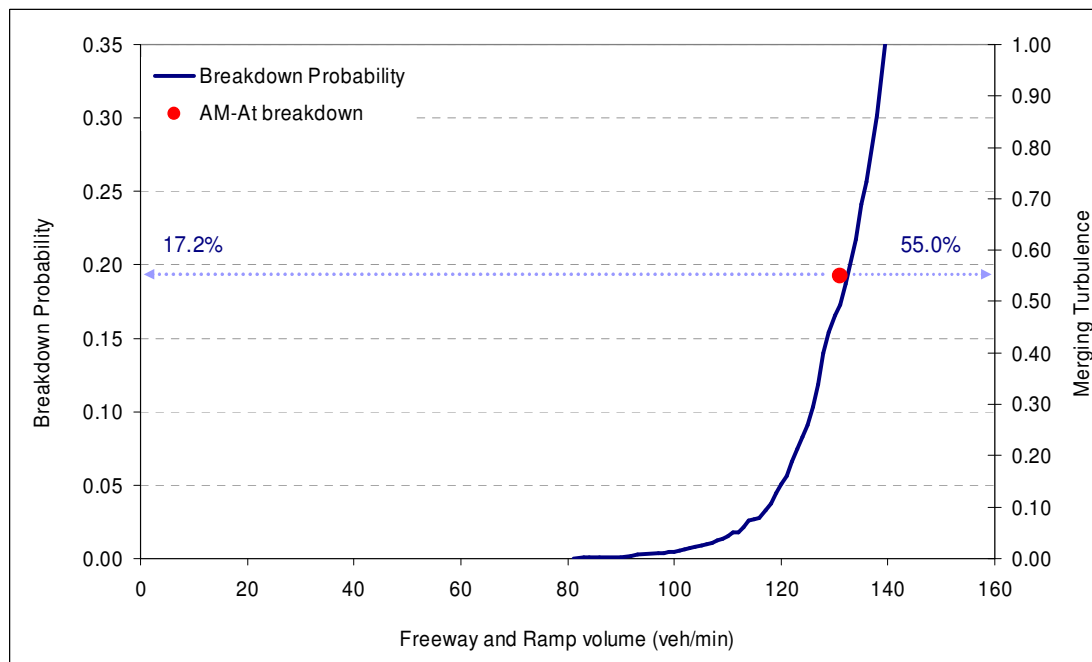


Figure 6-17. Breakdown probability model and merging turbulence.

Figure 6-17 also displays the merging turbulence for one breakdown event, based on the field data collection. The merging turbulence during the breakdown interval was 0.55 and it corresponds to breakdown probability of 17.2%. Additional breakdown-related data were not available, however, this graph shows the transferability of the breakdown probability model considering the two breakdown definitions. Future research direction should be towards the development of the breakdown probability model using the merging turbulence probability as the breakdown identification criterion.

Summary and Conclusions

This chapter presented a gap acceptance model under different merging conditions and a driver behavioral model that predicts freeway vehicles' interactions with the merging vehicles. Driver characteristics (aggressiveness) and their variation based on traffic conditions have been incorporated into both models. This chapter also presented the merging turbulence model which evaluates the effect of vehicle interactions at the merge area on the freeway flow. Field observations of one breakdown event showed that the merging turbulence increases before the breakdown and it could serve as an indicator for identification of the breakdown events.

The final conclusions with respect to the data analysis and the model development are offered here:

- The ramp design affects the merging position of the ramp vehicles. It was found that compared to parallel type on-ramps drivers used more length on the tapered on-ramps before merging. It was also found that the merging position on parallel on-ramps varies significantly, ranging from almost the end of the acceleration lane to even before the end of the solid white line.
- The gap acceptance model considers variations on the accepted gaps based on drivers' aggressiveness as well as the type of the merging maneuver. Drivers were grouped to aggressive and non-aggressive (average and conservative). It was found that aggressive drivers accept smaller gaps than non-aggressive, under cooperative and forced maneuvers. It was also found that the gap acceptance depends on the position of the ramp vehicle and its acceleration, and the traffic density.

- The freeway vehicle's decision to decelerate, change lanes or not provide any cooperation to the ramp vehicle was modeled as an MNL model. It was found that the freeway vehicles' decisions depend on the ramp vehicle's position on the acceleration lane, the distance with the ramp vehicle, the freeway density, and the number of vehicles on the ramp. The driver behavior types were grouped to conservative and non-conservative (aggressive and average).
- It was found that conservative drivers are more sensitive to their distance with the ramp vehicle than non-conservative drivers. Although they are less likely to cooperate compared to non-conservative drivers when the distance is large, they become increasingly concerned and try to change lanes when the distance decreases to avoid conflict with the merging vehicle.
- The forced merging assumes that all freeway vehicles will decelerate subject to the initiation of a forced maneuver. Aggressive and average driver types are included in this model since conservative drivers were not observed to perform forced merging maneuvers. The initiation of a forced maneuver depends on the ramp vehicle's aggressiveness and acceleration, its position on the acceleration lane, the number of ramp vehicles merging ahead and the freeway density.
- Although three driver types were initially considered, these were grouped into two categories for the model development. Also, for the models that describe the ramp vehicle's behavior drivers were grouped to aggressive and non-aggressive, whereas for the model that describes through drivers' behavior drivers were grouped to conservative and non-conservative. This may indicate that driver behavior changes depending on whether they are on the freeway or the on-ramp. This finding supports the focus group result, where it was found that drivers' aggressiveness depends on their task.
- Evaluation of the merging turbulence model suggests its correlation with the time to breakdown, as it was found to increase when the breakdown event was imminent, one to three minutes before the breakdown event (i.e., before a speed drop is recorded on the detectors).

The following recommendations are offered:

- The vehicle interactions and how these differ by driver type should be considered in developing or refining existing analytical or simulation models for freeway operations.
- The variation of driver types depending on their task should be incorporated to simulation models. This would also assist in developing more realistic tools for simulating the freeway flow breakdown.
- The merging turbulence model needs to be verified with additional breakdown observations. It is further recommended to use this measure for identifying and even predicting the time to breakdown.

CHAPTER 7 CONCLUSIONS

This chapter summarizes the research conducted in this thesis and presents the most important findings. Recommendations for future research are also offered.

Research Summary

A freeway-ramp merging model that considers vehicle interactions and their contribution to the beginning of congestion was presented. Focus group discussions were conducted to attain knowledge about drivers' thinking process when merging. There are three types of merging maneuvers (free, cooperative, and forced), based on the degree of interaction between the freeway and the ramp merging vehicle. Field data collection using an instrumented vehicle experiment was performed to observe drivers' merging process. Behavioral characteristics of the participants were also evaluated. The collected data were used for calibrating driver behavior models that pertain to their decisions to decelerate, change lanes or not interact subject to the ramp merging traffic, considering their behavioral attributes. A merging turbulence model was developed that captures the triggers for vehicle decelerations at the merging areas. The merging turbulence model due to vehicle interactions was evaluated through macroscopic observations at near-congested conditions. It was shown that the merging turbulence increases before the breakdown and it could be used as an indicator of the breakdown events.

Research Conclusions

The objective of this research was to develop a model that can capture vehicle interactions and determine the probability of breakdown on the freeway given the behavior of both mainline and ramp merging vehicles. The research conclusions based on the focus group discussions:

- Participants' responses were uniform with respect to the steps involved in merging, both for non-congested and congested conditions.

- Ramp design appears to affect drivers' merging process. Most of the participants indicated they would speed up and be more aggressive on taper ramps, compared to parallel design.
- Regarding gap acceptance, the participants would likely react differently, depending on which factors each one considers. Some drivers indicated that they might choose any gap (adjacent, upstream, or downstream), depending on the traffic conditions, while others would be less flexible. This searching and targeting of the surrounding gaps has also been described in Toledo (2003). Variables that affect gap acceptance have also been identified.
- Discussion on vehicle interactions showed that, if participants are on the freeway, their preference is to change lanes and avoid decelerating. If this cannot be accomplished, they will cooperate, depending on the speed/acceleration of the ramp vehicle, and its size/type. If the ramp vehicle attempts to force its way in, they will consider their distance to the upstream vehicle and the relative speed with the adjacent lane to decide whether to decelerate or change lanes. Ramp vehicle's decision to initiate a forced merge depends mostly on traffic-related factors, such as freeway speed, congestion and gap availability.
- Although the discussions captured a significant variability among participants', it is likely that their reported actions are different than their actual actions, depending on the values of each individual. For example, someone who values aggressiveness might respond as if he/she is aggressive.
- The stated driver actions were analyzed to identify differences in driver behavior. The criterion of "selfishness" was used to develop three behavioral categories: aggressive, average and conservative. Given this definition, the degree of aggressiveness of each driver varies as a function of their task and the traffic conditions.
- In congested conditions, driver behavior displays less variability; therefore, it may be more predictable. This is consistent with findings (Persaud and Hurdle, 1991; Cassidy and Bertini, 1999) indicating that the mean queue discharge flow displays smaller variability than other capacity-related measures, and remains consistent from day to day.

The following conclusions are offered based on the field data collection effort:

- The steps involved in the observed merging process are found to be quite similar with that identified during the focus group discussions (Chapter 4), for both congested and non-congested conditions.
- When participants were on the freeway they were involved only in free and cooperative merging maneuvers, and not in forced merges. Participants would show cooperation through lane changing more often than through decelerating. This indicates drivers' preference to change lanes if a gap is available. This finding is consistent with the relevant discussion from the focus groups.
- When the participants were the merging vehicle the majority of observed merging maneuvers were free. Cooperative and forced maneuvers were observed as well. When drivers' received cooperation from the freeway vehicles, usually this was through

deceleration rather than lane changing. However, it is possible that cooperative lane changes were not captured by the cameras since these would occur considerably upstream of the merge area. In this case they would be observed and characterized as free maneuvers.

- The participants' behavior was categorized as aggressive, average and conservative. Participants were categorized based on the criterion of "selfishness" as this was introduced in Chapter 4, and quantitative information about their speed and discretionary lane changing activity. Both assessments are consistent and come in agreement.
- There were few differences between the resulting driver type categorization and the participants' perceived aggressiveness. This inconsistency is most likely because participants responses may not be objective as will respond by comparing themselves with their peers.
- The resulting behavioral categorization showed that aggressive drivers belong to younger average age group category, compared to the other two types. Also, men were most likely to be aggressive than women.
- The field of view of the TMC cameras was very important for this study, as they dictate whether the locations of interest (e.g., bottlenecks) can be considered for data collection. However, there is a trade-off between the cameras field of view and the required zoom of the merge area to identify potential vehicle interactions and reactions. If more cameras were available, it would be possible to use multiple and capture the field of view with acceptable resolution upstream, at the merge and downstream of the merge area.
- The participation of actual drivers was a very challenging task of the data collection. This was primarily because several times drivers would fail to appear for the experiments, without any prior notification. In addition to that, obtaining drivers' thinking process was also challenging since drivers do not explicitly state their rationale behind their course of actions.

The conclusions related to the model development are summarized here:

- The ramp design affects the merging position of the ramp vehicles. It was found that compared to parallel type on-ramps drivers used more length on the tapered on-ramps before merging. It was also found that the merging position on parallel on-ramps varies significantly, ranging from almost the end of the acceleration lane to even before the end of the solid white line.
- The gap acceptance model considers variations on the accepted gaps based on drivers' aggressiveness as well as the type of the merging maneuver. Drivers were grouped to aggressive and non-aggressive (average and conservative). It was found that aggressive drivers accept smaller gaps than non-aggressive, under cooperative and forced maneuvers. It was also found that the gap acceptance depends on the position of the ramp vehicle and its acceleration, and the traffic density.

- The freeway vehicle's decision to decelerate, change lanes or not provide any cooperation to the ramp vehicle was modeled as an MNL model. It was found that the freeway vehicles' decisions depend on the ramp vehicle's position on the acceleration lane, the distance with the ramp vehicle, the freeway density, and the number of vehicles on the ramp. The driver behavior types were grouped to conservative and non-conservative (aggressive and average).
- It was found that conservative drivers are more sensitive to their distance with the ramp vehicle than non-conservative drivers. Although they are less likely to cooperate compared to non-conservative drivers when the distance is large, they become increasingly concerned and try to change lanes when the distance decreases to avoid conflict with the merging vehicle.
- The forced merging assumes that all freeway vehicles will decelerate subject to the initiation of a forced maneuver. Aggressive and average driver types are included in this model since conservative drivers were not observed to perform forced merging maneuvers. The initiation of a forced maneuver depends on the ramp vehicle's aggressiveness and acceleration, its position on the acceleration lane, the number of ramp vehicles merging ahead and the freeway density.
- Although three driver types were initially considered, these were grouped into two categories for the model development. Also, for the models that describe the ramp vehicle's behavior drivers were grouped to aggressive and non-aggressive, whereas for the model that describes through drivers' behavior drivers were grouped to conservative and non-conservative. This may indicate that driver behavior changes depending on whether they are on the freeway or the on-ramp. This finding supports the focus group result, where it was found that drivers' aggressiveness depends on their task.
- Evaluation of the merging turbulence model suggests its correlation with the time to breakdown, as it was found to increase when the breakdown event was imminent, one to three minutes before the breakdown event (i.e., before a speed drop is recorded on the detectors).

Future Research

The following recommendations and directions for future research are offered:

- The merging process from the driver's perspective as well as the vehicle interactions and how these differ by driver type should be considered in developing or refining existing analytical or simulation models for freeway operations.
- The variation of driver types depending on their task should be incorporated to simulation models. This would also assist in developing more realistic tools for simulating the freeway flow breakdown.
- Differences in attitudes and driver behavior between non-congested and congested conditions should be explicitly incorporated in traffic operational models.

- The merging turbulence model needs to be verified with additional breakdown observations. It is further recommended to use this measure for identifying and even predicting the time to breakdown.

APPENDIX A
PRESCREENING QUESTIONNAIRES

Focus Group Questionnaire



Prescreening Questionnaire for Merging Behavior Research

To Participants: This questionnaire is used to select a diverse pool of drivers to participate in the focus group experiment. Information collected in this form will be used for traffic engineering research only. All responses will be held in complete confidential and exempted from public disclosure by law. In accordance with the Confidential Information Protection and Statistical Efficiency Act of 2002 (Title 5 of Public Law 107-347) and other applicable Federal laws, your responses will not be disclosed in identifiable form without your consent. Since drivers' diversities are highly encouraged, only the most fitful responders will be chosen. Please answer as many as possible.

Return Address:

By Email: azk133@ufl.edu

By Mail: Alexandra Kondyli, 518C Weil Hall, PO Box 116580, Gainesville, FL 32601

1) What is your gender?

☐ Male ☐ Female

2) What is your age range?

☐ < 20 ☐ 20 to 29 years ☐ 30 to 39 years
☐ 30 to 39 years ☐ 50 to 59 years ☐ >= 60 years

3) Which of the following groups do you most identify yourself as?

☐ Caucasian ☐ Native American ☐ African American
☐ Hispanic
☐ Asian ☐ Pacific Islander ☐ Other _____
(please specify)

4) Where did you begin your driving practice and obtained your driver's license?

☐ North America ☐ Latin America ☐ Asia ☐ Europe
☐ Australia ☐ Other _____ (please specify)

5) How long have you been driving in the U.S.?

- ☐ < 1 year ☐ 1 to 3 years ☐ 3 to 9 years ☐ >= 10 years

6) Do you have a valid U.S. driver's license?

- ☒ Yes ☐ No

7) What is your occupation?

- ☐ Full time student ☐ University faculty/staff ☐ Professional driver
☐ Other _____ (please specify)

8) How often do you drive to work/school?

- ☐ Everyday ☐ Usually ☐ Sometimes ☐ Never

9) How much time do you spend driving per week?

- ☐ < 4hr ☐ 4 to 8 hr ☐ 8 to 14 hr ☐ > 14hr

10) What time of the day do you usually drive?

- ☐ Am/pm peak hour (6 am - 10 am; 4 pm - 7 pm) during work days
☐ Non-peak hours (including holiday and weekend)

11) What type of vehicle do you usually drive?

- ☐ Sedan/Coupe ☐ Pickup/SUV ☐ Jeep ☐ Truck

12) What time are you typically available for participating in the focus group experiments?

Please check as many as possible.

- | | |
|---|--|
| <input type="checkbox"/> Monday morning (9:00 am to 12:00 pm) | <input type="checkbox"/> Tuesday morning (9:00 am to 12:00 pm) |
| <input type="checkbox"/> Monday afternoon (1:00 pm to 4:00 pm) | <input type="checkbox"/> Tuesday afternoon (1:00 pm to 4:00 pm) |
| <input type="checkbox"/> Monday evening (4:00 pm to 7:00 pm) | <input type="checkbox"/> Tuesday evening (4:00 pm to 7:00 pm) |
| <input type="checkbox"/> Wednesday morning (9:00 am to 12:00 pm) | <input type="checkbox"/> Thursday morning (9:00 am to 12:00 pm) |
| <input type="checkbox"/> Wednesday afternoon (1:00 pm to 4:00 pm) | <input type="checkbox"/> Thursday afternoon (1:00 pm to 4:00 pm) |
| <input type="checkbox"/> Wednesday evening (4:00 pm to 7:00 pm) | <input type="checkbox"/> Thursday evening (4:00 pm to 7:00 pm) |
| <input type="checkbox"/> Friday morning (9:00 am to 12:00 pm) | <input type="checkbox"/> Saturday morning (9:00 am to 12:00 pm) |
| <input type="checkbox"/> Friday afternoon (1:00 pm to 4:00 pm) | <input type="checkbox"/> Saturday afternoon (1:00 pm to 4:00 pm) |
| <input type="checkbox"/> Friday evening (4:00 pm to 7:00 pm) | <input type="checkbox"/> Saturday evening (4:00 pm to 7:00 pm) |
| <input type="checkbox"/> Sunday morning (9:00 am to 12:00 pm) | |
| <input type="checkbox"/> Sunday afternoon (1:00 pm to 4:00 pm) | |
| <input type="checkbox"/> Sunday evening (4:00 pm to 7:00 pm) | |
| <input type="checkbox"/> Any time by appointment | |

13) Participant's contact information (at least 1 from phone/email/mail)

Name: _____ (Required)

Phone: _____

Email: _____

Date: _____

Mail Address: _____

Instrumented Vehicle Questionnaire



UNIVERSITY OF
FLORIDA

Transportation Research Center



Prescreening Questionnaire for Merging Behavior Research

To Participants: This questionnaire is used to select a diverse pool of drivers to participate in the 'in-vehicle' data collection experiment. Information collected in this form will be used for traffic engineering research only. All responses will be held in complete confidential and exempted from public disclosure by law. In accordance with the Confidential Information Protection and Statistical Efficiency Act of 2002 (Title 5 of Public Law 107-347) and other applicable Federal laws, your responses will not be disclosed in identifiable form without your consent. Since drivers' diversities are highly encouraged, only the most fitful responders will be chosen. Please answer as many as possible.

Return Address:

By Email: azk133@ufl.edu

By Mail: Alexandra Kondyli, 518C Weil Hall, PO Box 116580, Gainesville, FL 32601

14) What is your gender?

- ☐ Male ☐ Female

15) What is your age range?

- ☐ < 20 ☐ 20 to 29 years ☐ 30 to 39 years
☐ 30 to 39 years ☐ 50 to 59 years ☐ >= 60 years

16) Which of the following groups do you most identify yourself as?

- ☐ Caucasian ☐ Native American ☐ African American
☐ Hispanic
☐ Asian ☐ Pacific Islander ☐ Other _____
(please specify)

17) Where did you begin your driving practice and obtained your driver's license?

- ☐ North America ☐ Latin America ☐ Asia ☐ Europe
☐ Australia ☐ Other _____ (please specify)

18) How long have you been driving in the U.S.?

☐ < 1 year ☐ 1 to 3 years ☐ 3 to 9 years ☐ >= 10 years

19) Do you have a valid U.S. driver's license?

☐ Yes ☐ No

20) What is your occupation?

☐ Full time student ☐ University faculty/staff ☐ Professional driver

☐ Other _____ (please specify)

21) How often do you drive to work/school?

☐ Everyday ☐ Usually ☐ Sometimes ☐ Never

22) How much time do you spend driving per week?

☐ < 4hr ☐ 4 to 8 hr ☐ 8 to 14 hr ☐ > 14hr

23) What time of the day do you usually drive?

☐ Am/pm peak hour (6 am - 10 am; 4 pm - 7 pm) during work days

☐ Non-peak hours (including holiday and weekend)

24) What type of vehicle do you usually drive?

☐ Sedan/Coupe ☐ Pickup/SUV ☐ Jeep ☐ Truck

25) What time are you typically available for participating in these experiments? Please check as many as possible.

☐ Monday morning (6:00 am to 7:00 am)

☐ Monday evening (4:00 pm to 5:00 pm)

☐ Tuesday morning (6:00 am to 7:00 am)

☐ Tuesday evening (4:00 pm to 5:00 pm)

☐ Wednesday morning (6:00 am to 7:00 am)

☐ Wednesday evening (4:00 pm to 5:00 pm)

☐ Thursday morning (6:00 am to 7:00 am)

☐ Thursday evening (4:00 pm to 5:00 pm)

☐ Friday morning (6:00 am to 7:00 am)

☐ Friday evening (4:00 pm to 5:00 pm)

☐ Any time by appointment

26) Participant's contact information (at least 1 from phone/email/mail)

Name: _____ (Required)

Phone: _____

Email: _____

Date: _____

Mail Address: _____

Participants Background Survey



Participants' Background Survey Form

Participant's Name: _____

Date: _____

Note: Information collected in this form will be used for traffic engineering research only. All responses will be held in complete confidential and exempt from public disclosure by law. In accordance with the Confidential Information Protection and Statistical Efficiency Act of 2002 (Title 5 of Public Law 107-347) and other applicable Federal laws, your responses will not be disclosed in identifiable form without your consent. By law, every interviewer, as well as every agent, is subject to a jail term, a fine, or both if he or she makes public ANY identifiable information you reported.

27) If the speed limit on the freeway is 70 mph, what speed are you likely to drive (assuming good visibility and good weather conditions)?

☐ <65 mph ☐ 65 to 70 mph ☐ 70 to 75 mph ☐ 75 to 80 mph ☐ > 80 mph

28) How often do you change lanes if the vehicle in front of you is slower?

☐ Very often ☐ Sometimes ☐ Seldom

29) What type of driver do you consider your self?

☐ Very aggressive ☐ Somewhat aggressive ☐ Somewhat conservative ☐ Very conservative

30) What type of driver do your friends and family consider you?

☐ Very aggressive ☐ Somewhat aggressive ☐ Somewhat conservative ☐ Very conservative

31) When planning your driving trip, do you allow additional time for possible delays due to congestion, construction, or bad weather?

☐ Yes, always ☐ Sometimes

☐ Never

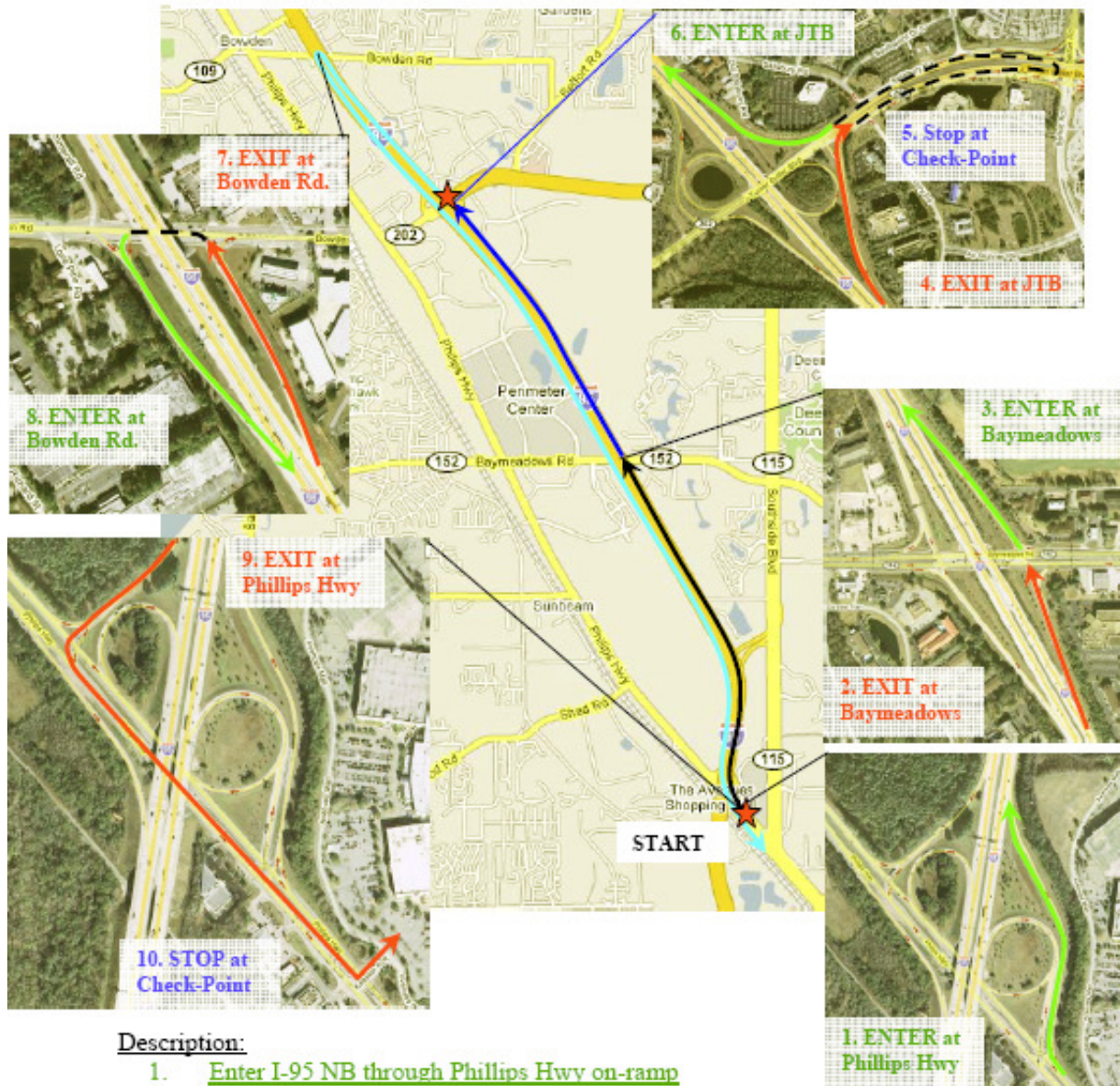
32) You are approaching the acceleration lane from an entrance ramp, and traffic has already started to appear on the freeway. When do you typically merge onto the freeway?

- ☐ Right after you enter the acceleration lane
- ☐ As soon as you see an appropriate gap on the freeway
- ☐ Just before you reach the end of the acceleration lane

- 33) You are driving in the right-most lane of a three-lane freeway and you are approaching an entrance ramp merge area. You can see that there are several vehicles entering the freeway from the entrance ramp. The vehicle in front of you changes lanes to avoid conflict with the merging vehicles. What do you do?
- ☐ Do the same – change lanes to avoid any interaction with the merging vehicles
 - ☐ Remain in your lane, but accelerate and close the gap between you and the vehicle further ahead, to discourage merging vehicles from cutting in front of you
 - ☐ Do nothing, and maintain your current speed
 - ☐ Slow down so that the vehicles from the entrance ramp can merge

APPENDIX B ROUTES FOR INSTRUMENTED VEHICLE EXPERIMENT

AM Route



Description:

1. Enter I-95 NB through Phillips Hwy on-ramp
2. Exit at Baymeadows Rd. off-ramp
3. Enter I-95 NB through Baymeadows Rd. on-ramp
4. Exit at J.T. Butler off-ramp
5. Stop at designated check-point on J.T. Butler Blvd.
6. Enter I-95 NB through J.T. Butler on-ramp
7. Exit at Bowden Rd.
8. Enter I-95 SB through Bowden Rd on-ramp
9. Exit at Phillips Hwy off-ramp
10. Stop at designated check-point on Phillips Hwy (The Avenues Shopping Mall parking lot)

PM Route



Description:

1. Enter I-95 SB through Bowden Rd on-ramp.
2. Exit at J.T. Butler Blvd off-ramp.
3. Enter I-95 SB through J.T. Butler Blvd on-ramp.
4. Exit at Baymeadows Rd.
5. Enter I-95 NB at Baymeadows Rd.
6. Exit at Bowden Rd. off-ramp.
7. Stop at designated check point on Bowden Rd. (parking lot)

APPENDIX C MEASURING LENGTHS ON DIGITAL IMAGES

The derivation of the correct scale for measuring lengths and distances from uncalibrated moving cameras is a difficult task, because the geometry of the road is constantly changing as the vehicle is traveling on the freeway segment. To address this issue, the method developed by Psarianos *et al.* (2001) is adopted. This method has been developed for measuring lane widths but it was modified to account for lengths along the road axis.

This basic geometry is described in Figure C-1, in which O is the perspective center and M is the image center.

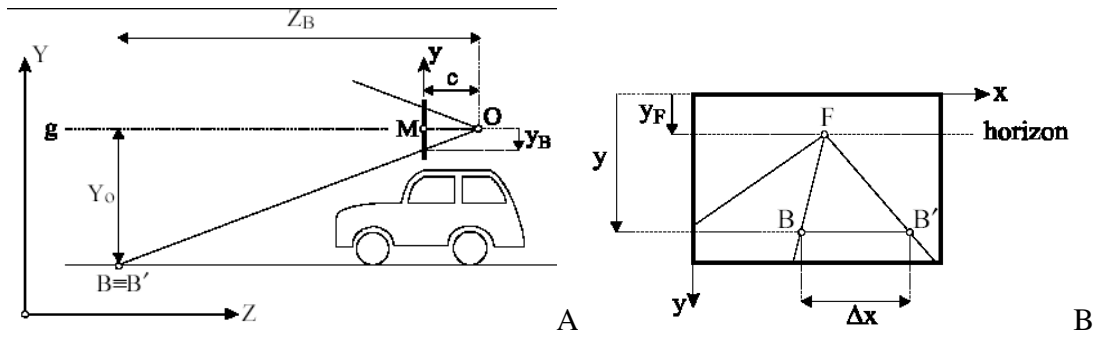


Figure C-1. Image geometry with A) horizontal camera axis and B) measurements on the digital image. (Source: Psarianos et al., 2001).

In Figure C-1 the camera constant is c , y_B is the y image coordinate of points B and B' on the road surface. If Y_0 is the camera height measured above ground level, then the scale of the image at a distance Z_B is:

$$\frac{c}{Z_B} = -\frac{y_B}{Y_0} = \frac{\Delta x_B}{\Delta X_B} \quad (C-1)$$

Where ΔX_B is the lane width BB' and Δx_B is the corresponding length measured in the image. Equation C-1 was used first to estimate the camera height Y_0 from known widths (range

from 6 to 20 ft) measured with a tape. The camera height for the front camera is estimated as $3.96 \text{ ft} \pm 0.30 \text{ ft}$. The camera height for the rear camera is estimated as $6.65 \text{ ft} \pm 0.50 \text{ ft}$.

Next, the camera constant c was estimated for both cameras given known lane widths ΔX_B and distances Z_B according to Equation C-2.

$$c = Z_B \frac{\Delta x_B}{\Delta X_B} = -Z_B \frac{y_B}{Y_0} \quad (\text{C-2})$$

Then, the constant c of the cameras was used for estimating the length Z_X from any point of the road X, by using the extracted images from the cameras.

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BIOGRAPHICAL SKETCH

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