

# A Framework for the Evaluation of System Safety Benefits of Intelligent Cruise Control Systems

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## ABSTRACT

This paper describes a framework for assessing the system safety impacts of an Adaptive or Intelligent Cruise Control (ICC) system. This framework incorporates a time-to-collision model that is developed from vehicle headway, speed, and acceleration data that are typically gathered as part of field operational tests. Specifically, the framework combines car-following models with vehicle deceleration and acceleration constraints to compute instantaneous rear-end time-to-collision estimates. These instantaneous time-to-collision estimates are then translated into an accident risk estimate that is accumulated over the entire trip. The proposed approach can be applied directly to field data that are typically gathered as part of field operational tests. In addition, the proposed approach can be easily incorporated within microscopic traffic simulation models.

## 1. INTRODUCTION

It is anticipated that the use of Intelligent Cruise Control (ICC) will, in addition to increasing the driver's convenience, produce impacts on safety, traffic flow, and the environment. This paper describes a proposed approach for assessing the safety impacts of ICC.

The core of the analysis that is presented in this paper is based on breaking down an entire traffic stream into pairs of vehicles. For these pairs of vehicles, potential trajectories for the lead and follower vehicle are first developed. These trajectories consider that the follower vehicle's behavior is dependent on that of the lead vehicle through a car-following relationship. In addition, the behavior of the follower vehicle may also be conditional on that of the lead vehicle in a mixture of stochastic and deterministic ways. Specifically, very attentive drivers are expected to react immediately to any changes in speed of a lead vehicle, while inattentive drivers may only react following a time lag (reaction time). When such a time lag is too long, given the initial vehicle spacing and relative speed and the resulting vehicle spacing at the conclusion of the reaction time could be such that a collision is inevitable.

This paper describes the proposed framework for the evaluation of the system safety impacts of an ICC system. The proposed framework is general in the sense that it can also be utilized to evaluate alternative Advanced Traveler Information System (ATIS) and Advanced Traffic Management System (ATMS) alternatives. Furthermore, the proposed safety model can be incorporated within microscopic traffic simulation models.

This paper first describes the unique features of alternative ICC system implementations together with the typical data that are gathered as part of field operational tests prior to discussing the

specifics of how the safety benefits of such systems can be evaluated. The paper then describes the proposed methodology together with some unique safety assessment considerations that are required in order to evaluate the system safety impacts of ICC systems. In the fifth section, the paper describes how the model can be calibrated using field data that are typically gathered as part of field operational tests. The sixth section describes how the proposed framework can be applied to evaluate the system safety impacts of ICC systems. The seventh section discusses how the market penetration impact on safety can be quantified using the proposed framework. Finally, the paper concludes with a discussion of future steps to enhance the proposed framework.

For the benefit of the reader, some terms that are subsequently utilized throughout the paper are defined first in Table 1. It should also be noted at this point that the term vehicle that is utilized in the paper refers to both the driver and the vehicle that is being driven in this paper.

**Table 1. Definition of Terms Utilized within the Description of the Approach**

<b>Term</b>	<b>Definition</b>
Model	A statistical, analytical or simulation technique for extrapolating or inferring findings. It represents a construct for deriving secondary findings from primary inputs.
Statistical Model	A model that has been calibrated by means of performing a parameter-fitting exercise. It represents a relationship that has been fit using statistical techniques to other data.
Analytical Model	A model for deriving results that implements a series of mathematical relationships. It represents a sequence of computations that is expressed in a simple flow chart.
Simulation Model	A much more complex model that derives and implements a more extensive set of rules. It derives emergent macro behavior from a set of micro behavior rules.
Pilot Test	A test with the actual FOT vehicle but by SAIC team employees. It usually involves a set of staged driving scenarios with extra data monitoring.
FOT Subjects	People recruited from the general population to drive the FOT vehicle. They drive the vehicle in a non-staged manner reflective of normal driving.
Time-to-collision	An estimate of the time to a potential collision, should a certain action be taken. No collision actually takes place, as drivers usually react to avoid a collision.
Accident Risk	An estimate of the potential probability for a collision per unit time or distance. No collision takes place, but the likelihood of a collision is estimated.
Vehicle Pair	A set of vehicles concurrently on the highway with no one in between them. The members of a pair are usually identified as a leader and follower.
Lead Vehicle	The first vehicle of a pair which is positioned ahead of a potential follower. No follower may actually be present behind the lead vehicle.
Follower Vehicle	The second vehicle of a pair which is positioned behind a potential leader. A lead vehicle has to be present in front of the follower vehicle.
ICC Vehicle	A vehicle with ICC-capable control and surveillance equipment on board. The ICC control equipment may not actually be actuated, however, the surveillance is always actuated.
Non-ICC Vehicle	A vehicle with no active ICC surveillance or control equipment on board. Activation is not an option available to the driver, and no data are collected.
Awareness	The extent to which a driver is alert with respect to the events that are occurring. A key pre-cursor to any driver response or reaction, following a given stimulus.
Reaction	The response of a driver to an external stimulus of which he/she has become aware. An activity that typically involves a series of coordinated actions
Exposure	A measure of the amount of time or distance a driver is exposed to a condition. Exposure is typically classified according to various attributes of the condition.
Time Horizon	A period into the future for which vehicle behavior and risk is extrapolated. A typical time horizon is 10 seconds.
Time Interval	A computational time step within the analysis of a time horizon. A typical time interval duration is one second.
Range	The distance between the rear of a leader and the front of a follower. Typically equal to a 'traffic engineering' distance headway minus the vehicle length.
Range Rate	The derivative of range with respect to time. Equivalent to the relative speed of two vehicles and their rate of closure.

## 2. TYPICAL INTELLIGENT CRUISE CONTROL SYSTEMS AND FIELD OPERATIONAL TESTS

Different forms of Adaptive and Intelligent Cruise Control (ICC) systems have been tested in the field. Some of these systems have braking capabilities incorporated within the system logic while others do not. The objective of this section is to describe the logic of some of the ICC systems that have been tested in the field prior describing how the safety benefits of such systems can be evaluated in the following sections. Furthermore, this section provides an overview of the typical data that are collected as part of field operational tests using the Ann Arbor field test as an example. Understanding the type of field data that are gathered is important in order develop an evaluation approach that is hinged on data that are readily available in the field.

### 2.1 ICC System Implementations

While conventional cruise control maintains a fixed vehicle speed during operation, the idea of the ICC system is to maintain a pre-selected headway distance (Martin, 1995). The ICC system that was tested in Ann Arbor, Michigan, for example, integrated a forward-looking sensor with a normal cruise control to automatically maintain a pre-specified headway between the ICC-equipped vehicle and the vehicle that preceded it. When other traffic were encountered, ICC-equipped drivers were relieved from engaging, disengaging, or manually resetting speed, as is required in conventional cruise control. While not in traffic, the ICC system acted as a conventional cruise control system (Koziol and Inman, 1997).

### 2.2 Typical Field Operational Test Data

This section describes the data that are gathered as part of the field operational tests with a focus on the field operational test in Ann Arbor, Michigan.

The Ann Arbor ICC field operational test was the result of a cooperative agreement between the National Highway Traffic Safety Administration (NHTSA) and the University of Michigan Transportation Research Institute (UMTRI). Other parties contributing to the field operational test were Leica AG, the Michigan Department of Transportation, and Haugen Associates.

For the ICC Operational Field Test (FOT), ten 1996 Chrysler Concordes were equipped with the ICC system. The ICC system consisted of the standard Chrysler cruise control; Leica sensors and intelligent (adaptive) cruise control logic and hardware; and a data acquisition system that collected data to support the evaluation. The data collection system collected video data and a variety of vehicle performance measures. The vehicle performance measures that were sampled 10 times per second (10 Hz) included the following:

- Range to the preceding vehicle,
- Rate of change in range to preceding vehicle (difference in vehicle speed between the ICC vehicle and the preceding vehicle),
- Vehicle velocity,
- Headway time selected by the driver,
- Vehicle heading,
- Curve radius, and
- Throttle setting.

One hundred and eight volunteers were recruited to drive ICC-equipped Chrysler Concordes for 2 or 5 weeks. Both groups of drivers experienced one week of driving the Concorde in a standard configuration (no ICC) before ICC functions were made available. The one-week without ICC was intended to provide baseline data for driving performance without ICC.

One and four week exposures to ICC were included in the research design to enable assessment of longer term changes in behavior as a function of experience with ICC. Other subject variables in the research design were:

- Driver age,
- Previous cruise control usage, and
- Driver type.

The 108 drivers were selected to include 66 drivers who had used cruise control before and 42 drivers who had not used cruise control before, as illustrated in Figure 1. These were further equally stratified by gender and by age group. Three age groups were considered, namely: 20 to 30 years old, 40 to 50 years old, and 60 to 70 years old. Figure 1 illustrates that the test participants were equally stratified by gender and age group in order to reduce the potential for systematic biases.

The 108 drivers, who were encouraged to drive as much as possible, drove a total of approximately 11,000 trips. During these trips the speed, acceleration and other measures (GPS coordinate, range, range rate, brake status, usage of the cruise control, etc.) of the ICC-equipped vehicle were recorded every deci-second.

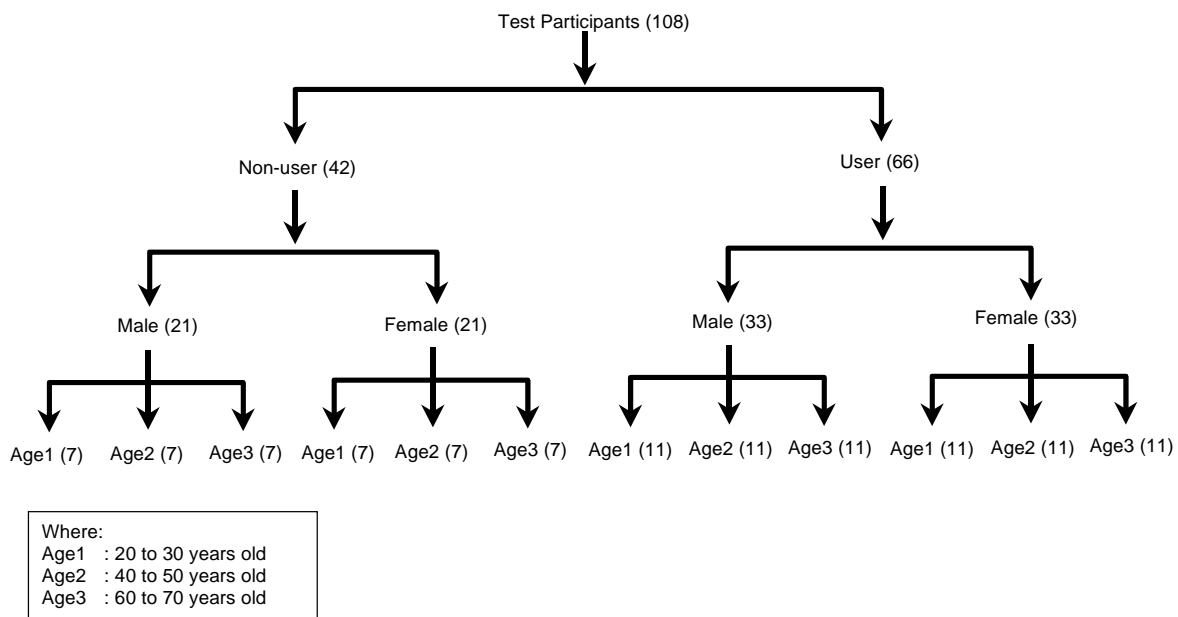


Figure 1: Stratification of ICC field operational test participants

### 3. ASSESSMENT METHODOLOGY

The proposed assessment methodology consists of five main activities that are performed sequentially. Different variations of the methodology are derived as a function of different ways in which these five main activities are performed, as indicated next.

The first activity in the analysis involves the decomposition of the traffic stream into a series of vehicle pairs, as illustrated in Figure 2. The vehicle pair attributes, such as the range and range rate, may either be derived directly from field data, or be derived from a simulation model, or may be hypothetical based on a series of roadway and fleet assumptions. Furthermore, the initial conditions of vehicle pairs may be identified as being associated with certain collision pre-cursor states, where the probability of being in such a pre-cursor state is determined external to this first step.

The second activity in the analysis involves the estimation of the potential time-to-collision associated with the current vehicle pair attributes, as illustrated in Figure 2. These attributes include driver reaction time, range, range rate, lead and follower vehicle acceleration rates, and a series of assumptions about how these parameters change within a foreseeable time horizon. The main variations to the second activity involve different assumptions with respect to the behavior, within the time horizon, of the lead and follower vehicle. Furthermore, these computations can be repeated fully each time they are needed, or they can be performed only once off-line, and then simply be referenced as needed in a look-up table.

The third activity of the analysis involves computing the rear-end accident risk that is associated with the time-to-collision estimate that was computed in the second activity.

The fourth activity in the analysis involves an aggregation of these vehicle pair risks, either across the entire fleet that is present on a section of the roadway network, and/or across some time horizon for which vehicle pairs are being tracked. This aggregation can either be performed within a simulation model that computes the initial risk estimates for each pair, or using an external enumeration method.

The fifth and final activity involves a conversion of the above-simulated rear-end accident risk into an actual accident risk, usually using a set of correction factors that have been derived by calibrating the estimated accident risk results against actual accident rate estimates, from the field, for comparable conditions. Furthermore, this activity also involves validating the accident risk by ensuring that pre-crash states are consistent between the analytical approach and field data. Analysis of the General Estimates System (GES) accident database demonstrates that approximately 27 percent of all accidents are rear-end accidents. Furthermore, of the rear-end accidents approximately 60 percent are rear-end collisions with stationary vehicles and 40 percent are rear-end collisions with moving vehicles. Consequently, given that ICC systems are unable to detect stopped vehicles, an ICC system can only impact approximately 11 percent ( $27 \times 0.4$ ) of the total number of accidents.

A typical execution of the above activities would involve replicating typical traffic conditions analytically using car-following characteristics that were observed in the FOT. The relative attributes of every vehicle pair would then be utilized to compute the potential for an accident occurrence within the next time horizon. All of these probabilities would then be summed for all of the vehicles on the section. The resulting accumulated simulated accident risk would then be

translated into a corresponding estimated actual risk based on correction factors that reflect known differences between actual and analytical accident risks.

A key factor to the above analysis is the identification of all of the important ways in which either the initial vehicle positions, or their subsequent hypothesized interactions, are different for vehicles in which the ICC unit is active, as indicated next.

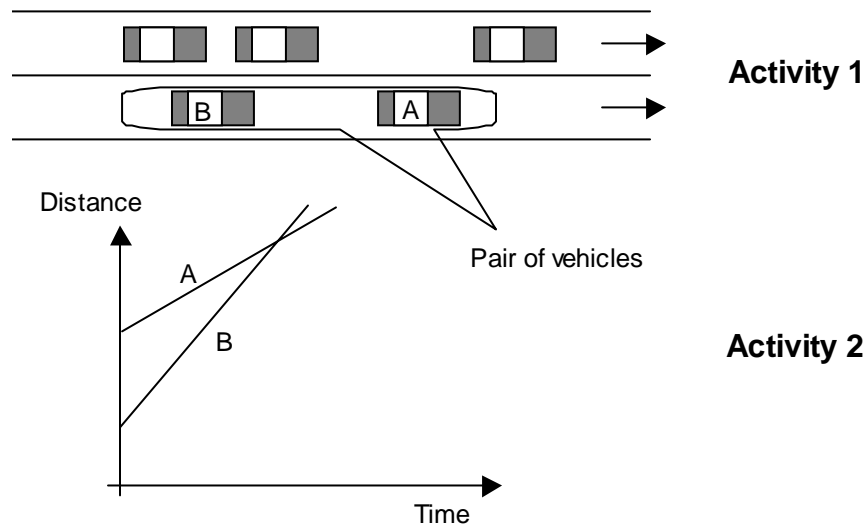


Figure 2: Illustration of first two activities of proposed methodology

#### 4. SAFETY ASSESSMENT CONSIDERATIONS

The systematic assessment of the differential safety implications of ICC system usage, according to the five steps that were defined earlier, requires the analysis of the following three main factors:

- a. the follower exposure factor,
- b. the awareness and response factor, and
- c. the leader exposure factor.

The first of these factors relates to the extent to which the ICC system tends to affect the risk exposure of the ICC-equipped vehicle. In other words, it relates to the extent to which the use of the ICC system tends to place vehicles into vehicle pair situations that are either riskier or safer to the ICC vehicle. This factor applies to potential collisions when the ICC-equipped vehicle follows another non-ICC vehicle. This factor is referred to as the follower exposure factor. Its primary consideration is to explore whether the use of ICC places that vehicle in pre-crash scenarios that are more or less risky, given that the ICC vehicle would have a similar awareness of and response to a certain lead vehicle stimulus. In terms of the discussion in section 1 of this paper, this assessment distinguishes the car-following behavior of the ICC-equipped vehicles from non-ICC-equipped vehicles.

Preliminary investigation into the car-following behavior of ICC using the Ann Arbor FOT and non-ICC-equipped vehicles does demonstrate potential differences. Specifically, Figure 3

illustrates a sample steady-state speed-headway relationship for non-ICC-equipped vehicles along the I-75 freeway in Detroit, while Figure 4 illustrates the typical steady-state speed-headway relationships that the ICC control algorithm attempts to maintain. Figure 5 illustrates some sample speed-headway relationships for different headway settings. Clearly, these preliminary relationships do demonstrate potential differences in the car-following behavior between ICC- and non-ICC-equipped vehicles. The safety implications of these differences need to be studied.

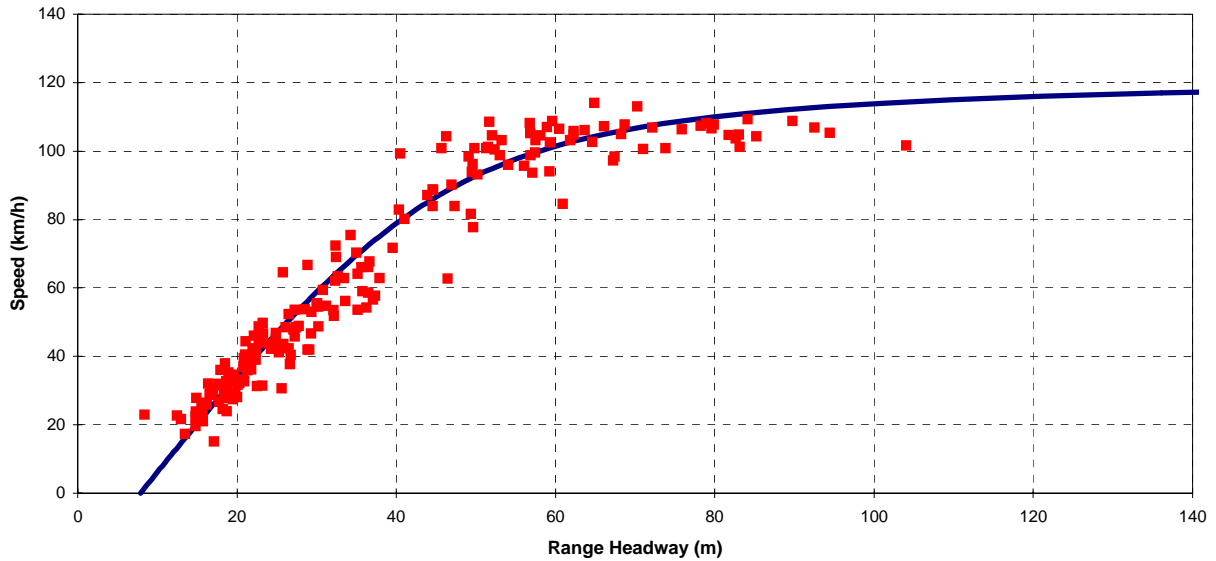


Figure 3. Sample steady-state speed-headway relationship (for I-75 Freeway in Detroit) (Source: Baker and Van Aerde, 1997)

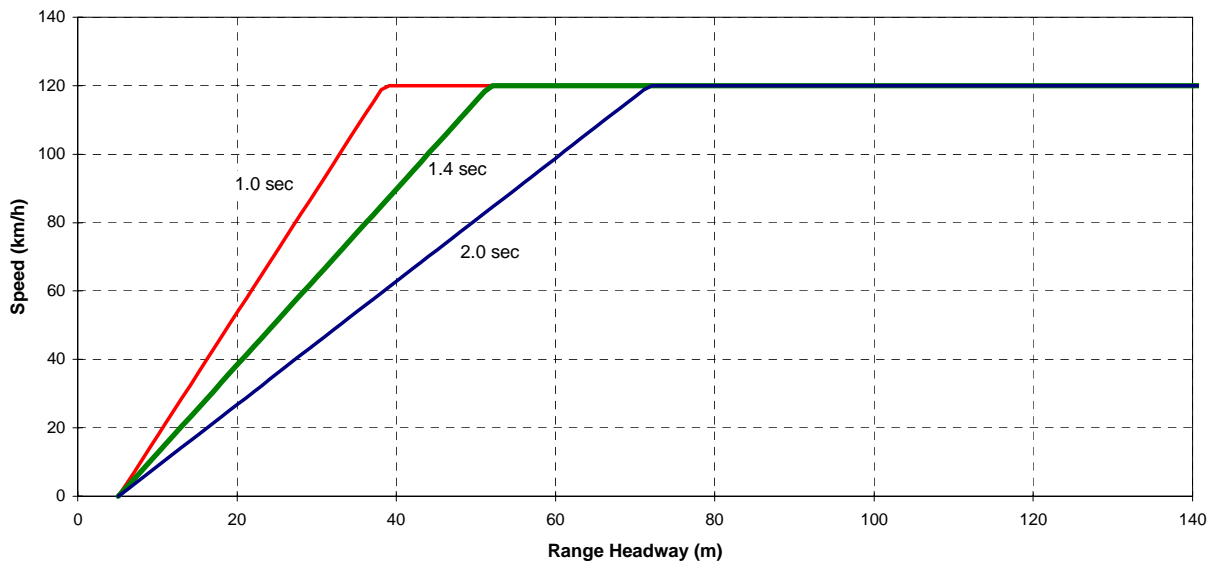


Figure 4. Desired steady-state speed-headway relationship of ICC control algorithm (Source: Baker and Van Aerde, 1997)

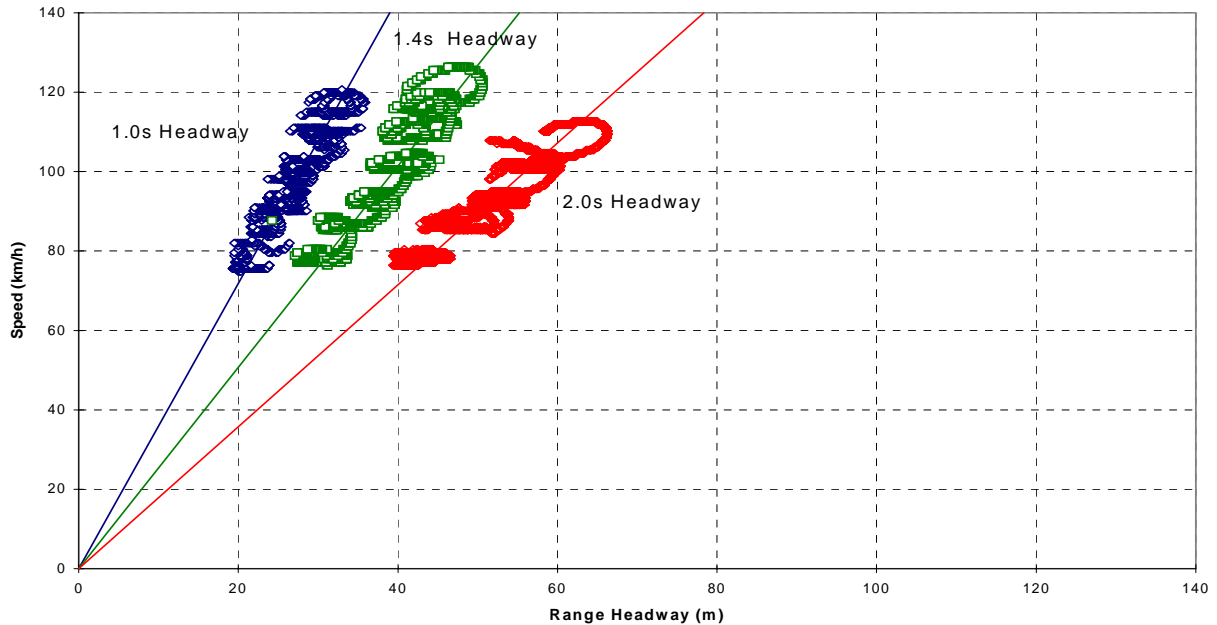


Figure 5. Observed steady-state speed-headway relationship of ICC control algorithm (Source: Baker and Van Aerde, 1997)

The second of these factors relates to the extent to which an ICC-equipped vehicle, when placed in a similar pre-crash scenario as a non-ICC vehicle, results in responses that involve greater or lesser accident risk. In other words, given an exhaustive range of well-defined but alternative pre-crash scenarios, is the reaction of an ICC-equipped vehicle expected to lead to a higher or lower probability of a collision? This assessment encompasses two different and distinct, but intimately highly interrelated, components. The first of these relates to any changes in the awareness and alertness of drivers to the traffic environment in which they are driving, with versus without ICC. The second component relates to the degree of difference of response of ICC-equipped vehicles, once a pre-crash scenario has evolved into a situation that requires direct intervention to avoid a potential crash. These two components are wrapped up into the combined awareness and response factor. In terms of the discussion in section 1, this factor relates to the extent to which an ICC follower vehicle, when starting out in a similar vehicle pair state, tends to behave differently within the subsequent time horizon analysis.

The third factor involves a consideration of the ICC leader, as opposed to follower, exposure factor. In other words, much of the earlier discussion has focused on how the use of ICC may affect the probability of an ICC-equipped follower vehicle crashing into another lead vehicle ahead of it. In contrast, this third factor considers the hypothesis that ICC usage may also affect differently the probability of the ICC vehicle being crashed into from behind. The basis of this particular hypothesis relates to the fact that, potentially, the differences in the speed and acceleration profile of an ICC vehicle may modify the mix of exposures to different pre-crash scenarios when an ICC vehicle is being followed by another vehicle. This analysis not only considers if the distribution of vehicle pairings in which the ICC vehicle is the leader is different than when a non-ICC vehicle is

the leader, but also considers how, within a given time horizon analysis, the behavior of an ICC lead vehicle may be different than that of a non-ICC leader.

The above three factors can then be applied to analyze any traffic flow when this traffic flow is broken down into one of four potential vehicle pair combinations, namely:

- a. an ICC vehicle following a non-ICC vehicle,
- b. an ICC vehicle following an ICC vehicle,
- c. a non-ICC vehicle following a non-ICC vehicle, and
- d. a non-ICC vehicle following an ICC vehicle.

It can be noted that the above four vehicle pair combinations together exhaustively represent all of the potential pairs of vehicle interactions that can arise in a traffic flow for all levels of market penetration of ICC, ranging from 0 to 100 percent usage of ICC, as noted next.

For example, at low levels of market penetration, the combinations of non-ICC vehicles following non-ICC vehicles clearly dominate. This would imply that most vehicle interactions would be of type (c), while combinations in which an ICC vehicle is either a follower or a leader (combinations (a) and (d)) would be relatively few. Furthermore, combinations where ICC vehicles follow other ICC vehicles (combination type (b)) would be rare.

However, at higher levels of market penetration, the mix of the above combinations becomes more balanced, creating situations in which an initial ICC vehicle (say, 1) followed by another ICC-equipped vehicle (say, 2) are much more common. Furthermore, the potential for a third ICC-equipped vehicle (say, 3) to be following both vehicles 1 and 2 becomes a plausible situation. It should be noted that some very simple statistical probability distributions could be utilized to determine the probabilities of each of these combinations occurring at each level of market penetration, at least if these probabilities are considered to be independent of differences in ICC versus non-ICC car-following logic.

For example, in a traffic stream consisting exclusively of non-ICC vehicles, all vehicle interactions would be of combination type (c). For a level of market penetration of 1%, the probability of combination type (c) still remains 98 percent, as combination types (a) and (d) now each come to have probabilities of 1% and 1%, respectively. Combination (b), however, now has a probability of 0.01% ( $0.01 \times 0.01 = 0.0001$ ), as it requires an ICC vehicle (probability 0.01) to be followed immediately by another ICC vehicle (probability 0.01).

The premise of the above analysis of unique vehicle pair combinations is as follows. If the response of an ICC-equipped follower vehicle is described for any set of lead vehicle characteristics (such as its relative position, speed, and acceleration), then the differences in the reactions of ICC-equipped follower vehicles to ICC versus non-ICC leaders become implicit rather than explicit. The same can be said about the response of non-ICC followers to either ICC-equipped or non-ICC-equipped leaders. In other words, if a model can be calibrated that shows how an ICC-equipped follower vehicle reacts to a lead vehicle's relative position, speed, and acceleration, then differences in follower reactions to ICC-equipped versus non-ICC-equipped leaders become emergent rather than hard-wired in the safety model. The same can, of course, also be said for the reactions of a non-ICC-equipped vehicle to either an ICC-equipped or non-ICC-equipped leader.

In summary, a safety assessment of ICC level of market penetration according to the previous section of this paper would consist of an assessment of an entire traffic stream on a vehicle pair basis. Each vehicle pair in the traffic stream would, at any instant, be associated with one of the above four combination types. In turn, for each vehicle pairing combination, there exists a current relative position, speed, and acceleration that can be interpreted as leading to a certain probability of a rear-end collision arising within a foreseeable future time window. These crash probabilities are closely tied to what the lead vehicle can be expected to do during this time window, and how the follower vehicle can be expected to react to the lead vehicle's actions.

Rear-end collisions would therefore become more likely as the lead vehicle behaves more erratically if the follower vehicle is at a closer initial headway (or range) when such erratic lead vehicle behavior occurs, or if the follower vehicle exhibits a more delayed or less appropriate reaction behavior. The premise of this analysis is that the magnitude of each of the above contributing factors can be measured and statistically tested in the field. Such measurement and testing requires the calibration of the above factors using field data, as is described next.

It should be noted at this point that the interaction of drivers and vehicles could be incorporated within the model by utilizing different reaction and response times. For example having older vehicles with male teenage drivers could be modeled as a different class of vehicles with its own reaction and response behavior.

## 5. SAFETY ASSESSMENT MODEL CALIBRATION

The above safety assessment considerations and hypotheses lead to the need for three main types of calibration analyses, namely:

- a. typical vehicle spacing,
- b. lead vehicle behavior characterization,
- c. follower vehicle exposure characterization,
- d. follower vehicle behavior characterization, and
- e. reaction time quantification.

### 5a. Typical Vehicle Spacing

The first characterization is to determine the typical spacing of vehicles as a function of the facility type (e.g. freeway), the level of congestion (defined by level of service), and the type of vehicle control (ICC versus non-ICC). This calibration exercise involves the use of field data collected as part of field operational tests. The characterization is important in order to define the initial conditions to be utilized in the analytical accident risk computation.

### 5b. Lead Vehicle Behavior Characterization

The second characterization basically involves determining the frequencies (or probabilities) associated with different lead vehicle behaviors, given an initial state. In other words, when a vehicle is a leader and driving at a certain speed at one specific instance, what are the probabilities that it will (within the next time horizon) either suddenly or gradually accelerate or decelerate? These probabilities are likely highly dependent upon the vehicle's initial speed, as well as the type of road facility it is driving upon and potentially the driver age, driver sex, and vehicle age.

Furthermore, it could be hypothesized that these probabilities are different for vehicles with and without ICC. It is important at this time to distinguish time intervals from horizons, as a horizon consists of many intervals. A typical horizon length is ten seconds, while a typical time interval is one second. The premise is that accident risks should be determined for a given time horizon by simply projecting forward lead and follower behavior one time interval at a time.

The first part of the above 'lead vehicle behavior characterization' is to determine these conditional probabilities for each potential speed change as a function of the vehicle's initial speed level. Subsequently, one then needs to determine if these conditional probabilities are statistically different for different road and vehicle characteristics. The assessment of different lead vehicle behavior, with and without ICC presence, simply explores if the presence of ICC makes for a lead vehicle target that is easier or more difficult to follow. It is anticipated here that the presence of ICC will smooth the vehicle's speed profile to such an extent that, all other things being equal, it is less likely to be hit from behind by another vehicle. Of course, it could be that most of the time, a lead vehicle's behavior is more gradual, but that at certain rare times, the delay deactivation of ICC may result in less safe lead vehicle behavior. It remains to be seen, therefore, if the potentially increased risk associated with these latter events offsets any decreased risk associated with the earlier events.

The outcome of this initial 'lead vehicle behavior characterization' is therefore be twofold. First, a multi-dimensional matrix is generated which describes how a vehicle's expected behavior in one time interval is probabilistically dependent upon that vehicle's behavior during the previous time interval. Secondly, a statistical determination is made to determine if ICC-equipped vehicles represent lead vehicle targets that behave differently, at statistically significant levels, from non-ICC-equipped lead vehicles.

### 5c. Follower Vehicle Exposure Characterization

The third calibration involves a 'follower vehicle exposure characterization.' In other words, it involves an assessment of the relative probabilities of a follower vehicle being in a certain follower mode relative to a lead vehicle. These probabilities are again expected to be conditional on a number of road- and vehicle-dependent factors, with the presence of ICC being a key vehicle-dependent factor. The result of this assessment is really a characterization of how often follower vehicles, whether ICC- or non-ICC-equipped, are in certain follower scenarios that can be identified as being pre-crash scenarios. An important general safety finding of this particular assessment is the relative probability of these pre-crash scenarios, as field data already exist that describe how often these pre-crash scenarios have preceded certain rear-end collisions.

A second, more important, ICC-specific finding is an assessment of any statistically significant differences in the frequency with which ICC- versus non-ICC-equipped vehicles are placed in these pre-crash scenarios. In other words, independent of how the presence of ICC may affect a follower vehicle's ability to react to a situation that involves intervention, it is important to first isolate how initial exposure to such events may be affected by ICC use. The premise is that differences in follower speeds, in headways, and in lane-changing behavior may actually modify pre-crash scenario exposure of ICC vehicles. This effect is independent of how the presence of ICC may also subsequently affect the response of vehicles when placed in similar pre-crash scenarios.

## 5d. Follower Vehicle Behavior Characterization

The fourth calibration involves a probabilistic characterization of car follower behavior. In other words, given a certain set of relative positions, speeds, and accelerations of a lead vehicle during one time interval, what are the probabilities associated with the expected accelerations and speeds of the follower vehicle during a subsequent time interval? This calibration involves the calibration of a probabilistic car-follower model that concurrently explores any differences in these probabilities for different road or vehicle types. In particular, differences in these probabilities for different road types would suggest facility-dependent reactions, while differences between vehicle types would indicate that the presence of ICC also modifies follower reaction probabilities.

The unique opportunity with an ICC field operational test database for performing the above calibration derives from the second-by-second logging of subject vehicle speeds, as well as the ranges and range rates relative to vehicles ahead of the subject vehicle. In other words, it is possible to calibrate the leader model by looking at all FOT data where the subject vehicle did not have a valid target ahead of it. For these conditions, a statistical analysis could be performed at any time,  $t$ , of what the vehicle was found to be doing at time  $t+1$ , which represents the end of one interval. By considering each time horizon to consist of multiple time intervals, one could project the behavior of a lead vehicle one time interval at a time. Furthermore, by determining if interval to interval behavior of ICC versus non-ICC vehicles is different, any differences could then be utilized to project differential behavior within the next time horizon.

The same linked time interval and time horizon analysis can also be applied to the follower vehicle. Specifically, given a certain follower range and range rate, the behavior of a follower in a subsequent time interval could be estimated with associated probabilities for each state at the end of the next time interval. Probabilistic estimates of how a follower vehicle reacts to a given lead vehicle's behavior within a given time interval could then be derived one time interval at a time.

The above leader and follower assessments indicate how a given initial state could, using FOT data, be extrapolated differently over the course of a time horizon, depending upon the attributes of the leader and follower vehicles. However, even the probability of being in a certain initial state can be determined from FOT field data, as statistical models describing how often a given pair of vehicles were following each other in a certain follower mode could be derived.

## 5e. Reaction Time Quantification

The final calibration involves calibrating the response and reaction distribution of ICC- and non-ICC-equipped vehicles. The calibration exercise involves usage of data from ICC field operational tests in order to compute differences between ICC- and non-ICC-equipped vehicles. Because the data that are collected as part of field operational tests do not typically include data at the extreme instances (prior to vehicle collisions), additional data from the literature and simulator data may also be included. Using the combination of literature, simulator, and ICC data, a reaction time model can be developed for ICC- and non-ICC-equipped vehicles. Again, differences in the age and gender of the driver together with the age of the vehicle should also be considered as potential factors that impact the response and reaction time.

## 6. SAFETY ASSESSMENT MODEL APPLICATION

The application of the above calibrated safety model components therefore involves the following five-step process for each vehicle pair:

- a. for every pre-crash scenario, probabilistically project the lead vehicle's path for the next time window,
- b. for the duration of the reaction time, assume the vehicle to continue maintaining its current speed and acceleration,
- c. after the conclusion of the reaction time, use the car-following model, constrained by the maximum acceleration/deceleration, to project the path of the follower vehicle for the remainder of the time horizon,
- d. given these combined probabilities of follower and lead vehicle paths together with the time-to-collision estimates, determine the associated probabilities of rear-end collisions and corresponding speed differentials at time of impact, and
- e. given the relative probabilities of different pre-crash scenarios, perform a weighted sum of all of the accident risks and severities for each pre-crash scenario.

The above assessment is performed four times, once for ICC following non-ICC, once for ICC following ICC, once for non-ICC following non-ICC, and one more time for non-ICC following an ICC-equipped vehicle. These four scenarios can be expressed more succinctly as NI, II, NN, and IN, where the first letter indicates whether the lead vehicle is ICC (I) or non-ICC (N), while the second letter uses the same code to indicate the status of the follower vehicle.

A qualitative description of this process runs as follows. First, consider a pair of vehicles traveling down the highway. Then project into the future, for an amount of time equal to the selected time horizon, what that lead vehicle is expected to do. Each such projection has associated with it a certain probability of occurrence. Furthermore, each projection involves a complete description of the lead vehicle's trajectory during this same time horizon. The projections of these vehicle trajectories are based on probabilities that have been calibrated in the field with respect to what a lead vehicle will do in any subsequent time interval, given a certain behavior in the previous time interval.

Next, consider each of the lead vehicle trajectories and examine for them what the potential actions might be of a follower vehicle. Again, based on field data, reaction times and car-following models are generated that describe how a follower vehicle may react to a given relative position, speed, and acceleration with respect to a lead vehicle. Each of these reactions results in a potential follower vehicle trajectory, which has associated with it a certain conditional probability of occurrence. Some of these follower trajectories reflect aggressive and immediate reactions of follower vehicles relative to a certain lead vehicle change in the trajectory. On the other hand, other reactions may result in either less aggressive and/or delayed reactions, each also with certain probabilities of occurrence.

The combination of rapid changes in lead vehicle trajectories, which have a certain probability of occurrence, together with delayed or inappropriate reactions of follower vehicles (which also have certain probabilities of occurrence), will together result in combined lead-follower trajectories that may intersect. The probability of such intersections is clearly dependent upon how far the vehicles

were initially separated, how often and dramatic the lead vehicle can be expected to change its trajectory, and how quickly and appropriately the follower vehicle is able to respond. Each of these probabilities is calibrated based on field data. Furthermore, the probabilities are weighted by the time-to-collision using weighting factors that are also calibrated based on field data. Clearly, an estimated time-to-collision of 1 second is more probable than an estimated time to-collision of 10 seconds because the vehicle will have time to respond in the latter case. Furthermore, the above trajectories can be utilized to not only derive a potential time-to-collision, but also a relative speed at the time of collision. This latter measure provides a surrogate for the expected severity of the expected collision.

The final outcome of the above analysis is a set of probabilities that describe how a certain combination of relative vehicle positions, speeds, and accelerations, at one instant in time, will lead to a range of rear-end potential collisions of differing severity within the prescribed time window. These probabilities will be road- and vehicle-specific in order to reflect differences in accident risk for different highway facility types, different levels of surrounding land use, and different drivers or vehicle controls. The magnitude of these latter differences, as well as the actual presence of these factors, is a direct result of the statistical analyses that are performed on the field data.

## 7. MARKET PENETRATION IMPACTS

The estimates of the ultimate market penetration impacts of the ICC technology are then based on an analytical procedure of different highways, for different levels of traffic demand, and for different levels of ICC market penetration. Each pair of follower and lead vehicles are examined to determine their accident risk, with respect to rear-end collisions, within the next time window. These risks are further weighted by the time-to-collision estimate and then summed for all vehicles that made such trips.

The net result of the above analysis is a series of accident risks as a function of a number of factors. Some of these factors relate directly to ICC usage while others do not. The extent to which the relationships of simulated accident risk map onto actual national accident rates for similar changes in non-ICC factors can be utilized to calibrate a translation relationship between simulated accident risk and actual accident rates. This translation relationship can then be used to translate ICC-based differences in simulated accident risks into estimates of actual changes in real accident rates. It should be noted that only the accidents that an ICC system can reduce should be included. This amounts to approximately 11 percent of all accidents as described earlier in this paper.

## 8. NEXT STEPS

The next steps to be taken in performing the network analysis can be characterized as follows:

- a. Accident pre-cursor event analysis,
- b. Probabilistic reaction time model development,
- c. Probabilistic car-following model development,
- d. ANOVA and F-test evaluation of ICC versus non-ICC differences,
- e. Collision probability and severity estimation
- f. Linkage of analytical to actual accident risks, and
- g. Market penetration impact assessment.

## 8a. Accident Pre-cursor Event Analysis

A set of conditional probabilities that specify the frequency with which certain types of rear-end collisions are preceded by different accident pre-cursor events has been developed by the Volpe Center. The first step in analyzing these scenarios is to develop a translation matrix that would map the ICC data onto these pre-cursor events.

The second step involves a computation of pre-cursor state exposure, where each pre-cursor state may actually include several sub-states that may be of interest in predicting differences in accident probabilities and severities. In other words, having identified which combination of FOT variable magnitudes correspond to which pre-cursor states, the next step is to analyze the FOT data in order to determine how often vehicles were in each of these states. This assessment is performed in such a way that differences in the type of vehicle control (ICC versus non-ICC), differences in the prevailing road type (e.g. freeway versus arterial), and differences in levels of congestion are reflected.

The result of this analysis is an assessment of how often vehicles, either with or without ICC, were in certain accident pre-cursor states. These probabilities therefore focus directly on the risk exposure factor, as it may be found that drivers who utilize ICC in circumstances where they previously did not, may experience different levels of relative exposure to pre-cursor events.

## 8b. Probabilistic Reaction Time

The reaction of a driver to a stimulus involves two inter-dependent variables. The first of these variables is the time lag between the occurrence of the stimulus and the driver's initial reaction to that stimulus. The second of these variables relates to how the driver responds to the stimulus. Clearly, both these activities involve a level of randomness that needs to be quantified.

For each of the above pre-cursor states, an assessment needs to be made as to the time lag that is associated with a driver's response to each pre-cursor stimulus. This assessment essentially involves looking at the relative speed, acceleration, and position of follower vehicles relative to a lead vehicle, and determining what that vehicle typically was doing each time interval after the lead vehicle was first observed. It is expected that several instances of observing an initial condition may lead to several different subsequent states. This analysis is performed by looking at the FOT data in each case two seconds at a time. The data during the first second represents the vehicle's initial state, while the data for the next second represents the state to which the vehicle transitions into. It is expected that the states may be different for different facility types, levels of congestion, and usage of ICC. Using these states, reaction times can be computed separately for each of the potential contributing factors. Given the large range of potential contributing factors, the intent is to initially consider that none of these factors have an effect, allowing all of the data to be pooled. Subsequently, one factor at a time will be considered as potentially having an impact. Once factors are identified that have an impact, the marginal impact of all other factors will be considered until no additional factors can be identified as having a statistically significant differential impact.

The inference within the above analysis is that if there are no statistically significant differences between the ICC and non-ICC vehicles, then ICC vehicles would be considered to react to stimuli the same way as non-ICC vehicles.

### 8c. Probabilistic Car-following Model Development

After an appropriate reaction time, drivers may react to a stimulus in different ways. The assumption is that drivers attempt to maintain a steady-state speed-headway relationship. Because of the randomness involved in driver reactions, there will be some form of distribution about the steady-state speed-headway distribution. Furthermore, the level of randomness may vary as a function of a number of factors including the type of control (ICC versus non-ICC), the facility type, and the level of congestion.

Using data gathered from the FOT confidence limits about the steady-state, speed-headway relationships will be generated for each of the potential contributing factors. Figure 6 illustrates an example steady-state speed-headway relationship (thin line) and the corresponding confidence limits (thick lines). In this example, it was assumed that there was no variability in the vehicle headways at jam density (speed equals zero), however, the variability increased as the headways increased.

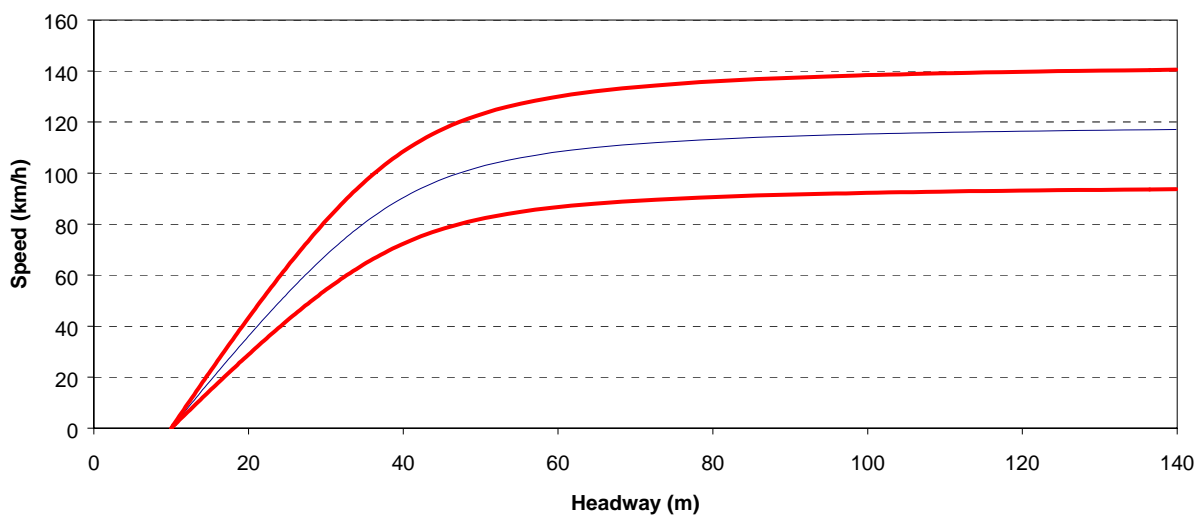


Figure 6. Example illustration of a probabilistic speed-headway relationship

### 8d. ANOVA and F-test analysis of ICC versus non-ICC Differences

The intent of the above exposure and response analyses was to provide different estimates for comparable conditions when vehicles were utilizing ICC and when they were not. The intent is to subject these differences to an Analysis of Variance examination. This ANOVA would determine if the differences in the mean between the reactions with ICC versus non-ICC were statistically different, at least when compared to differences that could be captured according to facility type, level of congestion, and any other factors that could be captured. This relative comparison is intended to not only quantify objectively the presence of an ICC versus a non-ICC effect, but it is also intended to place the magnitude of these potential effects into a context relative to other factors that are not related at all to ICC usage.

While the ANOVA compares the ICC versus non-ICC differences, it is limited in that it only compares the distribution means. It seems plausible that shapes of distributions may change and

variances may change. Consequently, non-parametric tests, as well as variance comparison tests (e.g. F-test) will also be considered in comparing differences between ICC and non-ICC vehicles.

## 8e. Collision Probability and Severity Measurement

The next step involves an estimate of the collision probability, and should it occur, an estimate of the relative collision severity. This estimate can be derived using a number of different methods, each applying the same underlying general methodology using different levels of approximation, as will be indicated next. The result of any of these analyses is a matrix *A*, which has as its rows a series of potential times-of-collision, ranging from 1 to 10 or more seconds. This same matrix *A* has as its columns a series of speed differentials at the estimated time-to-collision, where these speed differentials range from less than 10 km/h to more than 100 km/h. The cells in this matrix *A* would represent the probabilities that a rear-end collision would occur “*n*” seconds from now, and that this collision would have severity “*s*.” The accident risk will be computed using the probability that the two vehicle paths (lead and follower) intersect and weighted by the time at which the paths intersect (time-to-collision). A description of the details of the weighting by the estimated time-to-collision is beyond the scope of this paper, however, it will be described in a separate document.

A very simple way in which to populate this matrix is to utilize one of two potential deterministic approaches. The first of these considers that a pair of vehicles that is observed at any one instant will continue to travel at their current speeds, without the latter vehicle reacting at any time. An alternative deterministic solution is one in which a given pair of vehicles continue to accelerate or decelerate at the same rate that they are traveling when they are first observed. Either one of these solutions would result in a probability of 100% of a collision either occurring or not occurring within the given time horizon. Furthermore, given a certain 100% probability of that collision occurring “*n*” seconds from now, there would be complete certainty as to the relative speed at the time of this collision.

A more realistic stochastic approach is to assume that either the lead vehicle or the follower vehicle has a certain probability of accelerating or decelerating at a certain rate, and that there is a consistent probability of when during that time horizon the reaction first occurs. The result of this analysis is the decomposition of each lead and follower vehicle action into an estimate of a time-to-collision and a corresponding differential speed (severity) at the time of collision. The entry into matrix *A* would therefore be a series of probabilities associated with each potential time-to-collision and speed differential that is associated with a certain set of lead and follower vehicle assumptions. The actual probability magnitude in this case is the joint probability of occurrence of that lead and follower vehicle assumption weighted by the time-to-collision. The probability of certain lead vehicle and follower vehicle responses would be derived from FOT data.

## 8f. Linkage of Simulated to Actual Risk

The next step in the analysis is the linkage of simulated to actual risk, where the simulated risk can be derived from two main comparable sources. The first of these is an analytical solution in which the time-to-collision and associated collision severity matrix for each accident pre-cursor state are summed up using a time-to-collision weighted average. The particular weights are derived by considering the relative probability of certain accident pre-cursor probabilities occurring, as found in the FOT data. The second source is an on-line computation of the probability matrices within a microscopic traffic simulation. This latter simulation would consider the probability of collision

(and associated severity) for each vehicle pair every second of the simulation, and simply sum up all of those probabilities for all vehicles and the entire simulation period.

Independent of whether the above computations are from an analytical or simulation model, the result is an expected matrix for the entire fleet of different times-to-collision and associated severities. The intent is then to derive these matrices for different scenarios for which accident risk is known, and then to calibrate a translation matrix from analytical or simulation risk to actual field risk. The intent of this calibration is to then have a set of correction factors that translate the analytical or simulated risk into actual risk for analyses where simulated risk estimates are possible, but where observed risk estimates are not available.

The ICC system will not prevent all rear-end accidents from occurring even if the entire fleet were ICC vehicles (100 percent market penetration). There are numerous rear-end accidents that the ICC system would not prevent, like for example, a rear end collision to a stopped vehicle (approximately 60 percent of all rear-end accidents), or an accident caused by a person changing lanes, or a driver not being attentive. The former accident type can be accounted for by using the GSE accident statistics, which indicates that 60 percent of all rear-end accidents occur when the lead vehicle is stopped. It would be practically impossible to account for the latter accident types given that the accident databases do not indicate what portion of rear-end accidents are associated with vehicles making lane changes or drivers being inattentive. It seems that the only way to account for these factors will be through the calibration of the accident risk to actual field data.

#### 8g. Estimation of Level of Market Penetration Effects

The final Level of Market Penetration Analysis is based on either a comparable analytical or simulation effort, as indicated next.

The analytical effort consists of determining how, for a certain traffic stream, the frequency of combinations involving non-ICC following ICC, non-ICC following non-ICC, ICC following non-ICC, and ICC following ICC will change. For each of these combinations, estimates of being in certain accident pre-cursor states would be developed, and finally, for each of these accident pre-cursor states, different time to collision and severity of collision probabilities would be estimated. The sum of the resulting overall cross products of each of these three elements would then represent the net 'modeled' accident risk for each of the potential levels of market penetration. These modeled accident risks would then need to be translated one more time into expected actual accident risks based on a process that was described above.

A parallel path to the above analytical solution is a simulation solution. In this case, the probability of time to collision and associated collision severity would again be computed for each vehicle pair every second, but the identification of pre-cursor event states and the relative probability of occurrence would not need to be computed a priori. Instead, the simulation model would place ICC and non-ICC vehicles in the appropriate states, with appropriate probabilities, allowing a simple sum of accident risk across the entire fleet and the entire simulation period to be performed. However, similar to the above analytical estimates of accident risk, a translation of simulated to actual accident risk would need to be performed at the conclusion of the simulation.

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