A NOVEL METHOD TO EVALUATE THE SAFETY OF HIGHLY AUTOMATED VEHICLES

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ABSTRACT

Highly automated vehicles are expected to perform ordinary driving tasks as well as improve safety, in emergency situations when in their desired domain of operation. This poses challenges in testing such systems. Conventional methods of testing, which recreate specific scenarios may address some emergency situations but simply do not cover all the scenarios a highly automated vehicle is expected to handle.

This paper proposes a method that can be applied to normal driving that quantifies risk at any instance. This method analyzes the current situation to determine the probability of an unavoidable collision occurring. This probability is described as an Instantaneous Safety Metric (ISM). This type of evaluation allows for the presence of traffic configurations with a high collision probability to be identified at any point in time, and even if no collision occurs.

Simple vehicle models are used to project possible future positions of each vehicle in a scenario and the probability of a crash estimated. This document presents results from development of this method, to this point, and the current view of a path to completion.

INTRODUCTION

Challenges in Applying Traditional Testing Procedures to Automation Systems

Development of a testing procedure for high-level vehicle automation systems presents unique challenges when compared with those developed for more conventional safety systems. Typically, test procedure development begins by selecting a set of scenarios in which the system is designed to improve safety. Next, vehicles are tested in those scenarios, and results are analyzed to quantify whether or not the outcome was improved. Finally, the results are compared with a developed set of criteria which regulators use to classify system performance [1] [2].

Two main challenges are present in applying this type of process to highly automated vehicles.

First, a highly automated vehicle should respond appropriately to any situation possible in the desired space of operation. Therefore, a large number of tests are required to gain appropriate coverage over this space of possibility. This challenge can be addressed either by brute force, through a large amount of physical testing, or by testing algorithms in a validated simulation environment, greatly improving cycle time.

Second, the level of safety in a given scenario cannot solely be quantified by looking at the occurrence or severity of collisions. A discrete set of tests cannot cover the continuous space of possibility. Therefore, situations producing a “near miss” must also be analyzed. This analysis calculates the probability of a collision occurring had the parameters been varied slightly. Addressing the challenge of evaluating safety requires a fundamental change in the way safety system performance is quantified.

Fundamental Questions

The fundamental concepts of the ISM approach can be explained through a series of simple questions about one’s current situation while driving:

1. What set of actions could other vehicles around me choose, and how do those actions effect my decisions?
2. If other drivers could choose any control input possible, what is the resulting range of positions and orientations?
3. If the vehicles around me pursue any combination of these actions do I have an escape path, and would severe maneuvering be required?

Going through these questions, it is clear that for any situation a vehicle is in, the possibility of a collision with another vehicle can be calculated by considering all possible movements of all the vehicles around it. To better understand this concept, a simplified case is discussed in the following section.

Simplified Case Study

A basic case study in which the driver is limited to four actions is used to illustrate how this approach provides information on vehicle safety. These actions consist of:

- Full longitudinal acceleration
- Full longitudinal deceleration
- Full lateral acceleration to the left
- Full lateral acceleration to the right

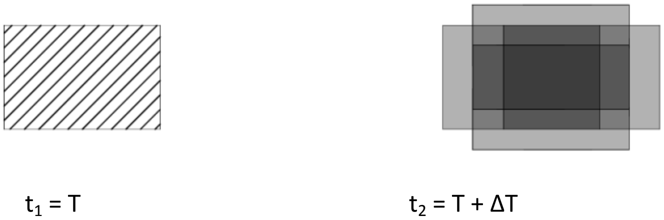


Figure 1. Possible future positions for four basic control actions

In Figure 1, the diagonally lined rectangle represents the initial position, orientation and shape of the subject vehicle. The four gray rectangles illustrate the possible positions at some point in the future (time t_2), each rectangle corresponding to one of the above mentioned actions.

Two important observations emerge from Figure 1. The first is that, this vehicle only needs to be concerned with objects that could be within the grey region of space at time t_2. Therefore, other objects which cannot be in the specified region of space, at time t_2, can be ignored in analyzing this specific point in the future. Second, there is an area which intersects all four resulting positions at t_2, shown as the dark center square in Figure 1. This is a space the vehicle cannot avoid, i.e. some part of the vehicle will be present in that region at time t_2. Consequently, if a vehicle or object is capable of being in that region at the considered point in time, this set of choices could not avoid that object.

Though this case is fairly simple, these observations can be expanded to sets of actions covering the full space of possibility.

Prior Work in Trajectory Planning

Approaches similar to that used in this document have been used in trajectory planning. These methods vary in their implementation but many contain elements related to the current direction of this work. Many of these methods look at threat assessment by determining if the subject vehicle has an escape path in the current situation [3] [4]. Others look at the possibility and probability of certain courses of action to compare various path options [5] [6] [7] [8]. While, some of these methods quantify threat level in specific cases by looking at prior experiences in similar cases [9] [10].

DEFINITIONS OF IMPORTANT SPATIAL REGIONS

The observations from the prior section are formalized using the following definitions. These definitions aid in communicating these concepts and in classifying interactions between vehicles.

Reachable Set

The reachable set consists of all possible positions and headings a vehicle can achieve at a particular point in the future. This is most commonly represented in implementation by a set of discrete points which each have the form (X, Y, Ψ). Where X and Y are the position and Ψ is the heading.

Profile

The resulting region when the vehicle geometry is placed according to a member of a reachable set.

Possible Space

The possible space is the boundary of the region the vehicle can exist in at a given point in time. This is equivalent to the union of all profiles for the subject vehicle's reachable set at that point in the future. An example representation of this space's boundary is shown as the dashed line in Figure 2. If we look far enough into the future, we expect that the vehicle could be anywhere. Therefore, we expect this space to grow and trend toward infinity with time.

Unavoidable Space

Following the concepts from the prior section, the intersection of all profiles at a given point in the future, is also important in interaction analysis. This region is termed the "unavoidable space" and is defined as the region in which some part of the vehicle must exist at a particular point in the future. This region is the dark grey region in the simple case considered in Figure 1. The solid line in Figure 2 is the boundary of the unavoidable space. As we look further into the future, this unavoidable space decreases in size. The size of the vehicle is finite therefore the time for this to disappear must also be finite. Though not directly related to the disappearance of this region, this behavior indicates that there exists a duration of time after which all interactions are avoidable.

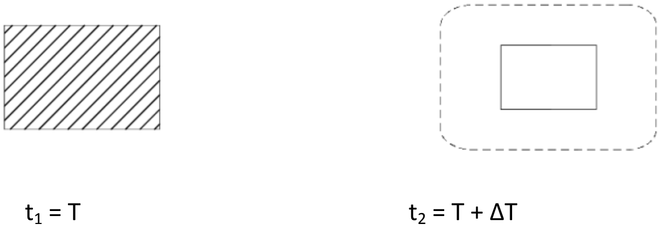


Figure 2. Example plot of Possible and Unavoidable spaces

INTERACTION OF DEFINED REGIONS

Interaction between vehicles, for analysis sake can be treated as interaction between profiles. Analysis of the basic interaction of two vehicles is used to demonstrate interaction concepts that can be extrapolated to multiple vehicles. These vehicles are referred to as Vehicles A and B. Each of these vehicles has their own possible and unavoidable spaces, which results in four different possible relationships between these vehicles. Currently this approach does not consider other objects on the road but could easily be expanded to do so (e.g. a stationary object can be modeled similar to a stopped vehicle with no acceleration authority).

- There is no overlap between either vehicle's possible spaces. Therefore, these vehicles cannot make contact at the currently considered point in the future. This is classified as an "Impossible Interaction" case.
- There exists overlap between the possible spaces of the two vehicles. This implies that there is a set of decisions that can be made between the two drivers that would result in these vehicles making contact, but it may not be possible for either vehicle to make this decision unilaterally. This is classified as a "Possible Interaction" case.

- There is a region of overlap between the unavoidable space of Vehicle A/B and the possible space of Vehicle B/A. This indicates that Vehicle B/A can pursue a course of action which is unavoidable by Vehicle A/B. In this case Vehicle A/B has ceded control of the scenarios outcome to Vehicle B/A. This is classified as a “Critical Interaction” case. The interaction discussed above is a sufficient but not necessary condition for a critical interaction.
- The unavoidable space of Vehicle A overlaps the unavoidable space of Vehicle B. The presence of this interaction implies that regardless of the actions of either vehicle, contact between the two is going to occur. This is classified as an “Imminent Interaction” case. Similar to the critical interaction example above, this is a sufficient but not necessary condition for an imminent interaction.

This procedure is designed to test a single vehicle’s automation algorithm; therefore, some of the generality of terms can be reduced by naming vehicles in a manner consistent with this intention. The vehicle under test is referred to as the subject vehicle, while all other vehicles in the domain are referred to as traffic vehicles.

The definitions of the possible and unavoidable regions, provide a convenient framework for discussion, but do not provide enough information for the necessary conditions for these interactions. The necessary conditions are listed in the following section.

Impossible Interaction – Vehicles cannot make contact at the currently considered point in the future.

Possible Interaction – Vehicles can make contact at the currently considered point in the future for at least one set of driver inputs.

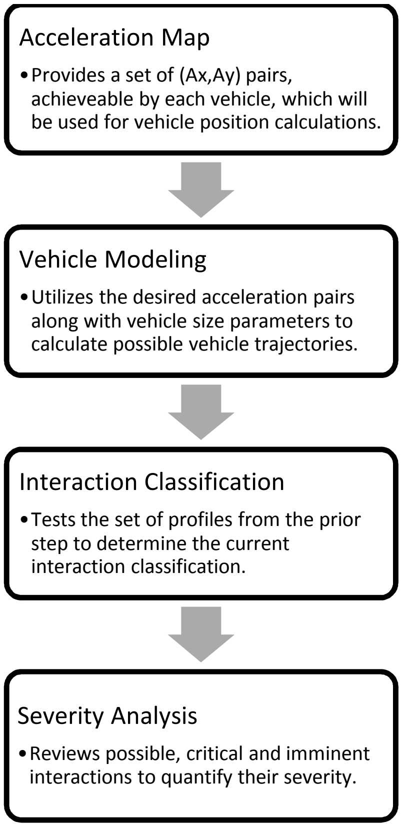
Critical Interaction – There exists a set of profiles for the traffic vehicle or vehicles which contact all profiles for the subject vehicle at a particular point in the future.

Imminent Interaction – All possible actions by traffic vehicles result in contact occurring with the subject vehicle at some point in the future.

PRACTICAL IMPLEMENTATION OF INTERACTION CLASSIFICATION

Using these definitions, an implementation of this method, such that interactions can be classified in near real time is being devised. The details of this method are still being refined. For this reason, the presentation of the current method solely provides insight into the direction of the work and is a tool for discussion of this concept.

Figure 3 shows the overall flow of the current ISM implementation. The following sections discuss in detail the purpose of these modules and some of their technical details.



- Provides a set of (Ax,Ay) pairs, achieveable by each vehicle, which will be used for vehicle position calculations.
- Utilizes the desired acceleration pairs along with vehicle size parameters to calculate possible vehicle trajectories.
- Tests the set of profiles from the prior step to determine the current interaction classification.
- Reviews possible, critical and imminent interactions to quantify their severity.

Figure 3. ISM process flow chart

Acceleration Map

In vehicle dynamics, combined vehicle longitudinal and lateral acceleration limits are plotted in a two-dimensional plane called the g-g diagram [11]. The boundary of this region indicates the limits of vehicle control ability but any point within this region is also equally valid. This behavior is commonly modeled as an ellipse or other similar function. The ellipse is defined by X and Y axis intersection points being the maximum longitudinal and lateral accelerations respectively, and where each point on the boundary of the ellipse represents tire force saturation. Figure 4 shows an ellipse parameterized for this purpose.

Interaction classification (possible, critical, imminent, etc.) can be done by solely using points on the edge of the ellipse. Though, the current algorithm utilizes a vector of acceleration pairs (A_x, A_y) which represents both the boundary and the center of the ellipse. This enables the testing of some proposed methods of severity analysis presented later in this document.

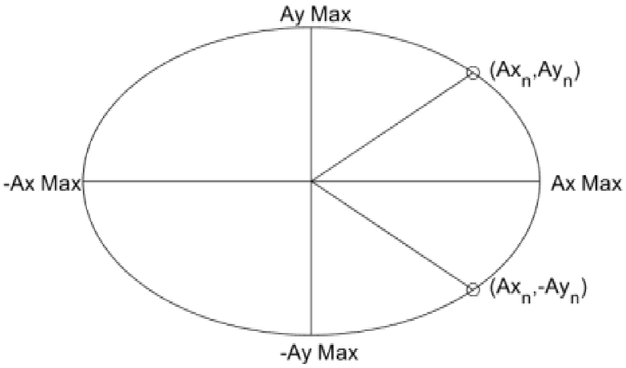


Figure 4. Parameterized acceleration ellipse

Vehicle Modeling

Selecting a vehicle model for use in this application is constrained by the set of available parameters. Essentially, this model needs to be able to calculate a vehicle's possible future positions with information obtained solely from "looking" at it.

The selected model is developed based on parameters which can be measured remotely, for example distances and sizes, while avoiding parameters which could not be externally quantified, e.g. mass and inertia. The requirement of having a model with no mass properties largely limits the available modeling techniques. One technique which fits these requirements is a kinematic version of the bicycle model [12]. This type of model is ideal for this application due to only requiring parameters of vehicle wheelbase and maximum road wheel angle.

The formulation of this model is based on inputting a set of lateral and longitudinal accelerations from the acceleration map into the model. The model will generate these accelerations except at low speeds when the model is limited by the maximum steering angle. At higher speeds the model is no longer limited by steering angle and therefore can achieve the desired lateral acceleration. The use of such a model is currently being validated.

Interaction Classification

The previously discussed interaction classification concepts are useful illustratively, but as discussed, a more robust method of achieving a similar result is applied in the current implementation. The algorithm being developed for interaction classification starts by comparing the set of profiles for the subject vehicle with the set of profiles for the traffic vehicle. This process results in an overlap matrix for the current point in time (t_p).

In the overlap matrix, shown as Equation 1, the value of the element $I_{M,N}^{t_p}$ is a Boolean which indicates whether or not the M$^{\text{th}}$ profile for the traffic vehicle overlaps the N$^{\text{th}}$ profile for the subject vehicles at t_p seconds into the future. In this framework a possible interaction is indicated by the presence of a true value at any location in this matrix. Similarly, a critical interaction is indicated by the presence of a row in which all values are true. This is linked directly back to the original definition in that it indicates that there is at least one action for the traffic vehicle which overlaps all possible actions of the subject vehicle. An imminent interaction in this case would be indicated by all values of this matrix being true.

$$\begin{array}{cc}
 & \xrightarrow{\text{Subject Vehicle}} \\
\text{Traffic}\big\downarrow & \begin{bmatrix} I_{1,1}^{t_p} & I_{1,2}^{t_p} & \cdots & I_{1,N}^{t_p} \\ I_{2,1}^{t_p} & I_{2,2}^{t_p} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ I_{M,1}^{t_p} & \cdots & \cdots & I_{M,N}^{t_p} \end{bmatrix}^{N\,x\,M}
\end{array}$$

(Equation 1)

It is important to remember that this matrix represents only one point in time and the interaction of two vehicles. The presence of critical or imminent interaction based on the above matrix is a sufficient but not a necessary condition for these types of interactions. Critical or imminent interactions are not limited to occurring at a single prediction time or only between two vehicles. Therefore, a negative result at this stage does not prove the lack of existence of either type of interaction. Interactions for multiple vehicles or for multiple prediction times can combine to result in critical or imminent interactions which are not present in the single case.

Multi-Time Interactions

As previously stated an interaction being non-critical or non-imminent at a single point in time does not prove that the combination of events through time do not fall into these categories. These cases generally occur when a profile associated with one decision can only be reached by passing through another traffic profile at an earlier instance in time. This condition would typically mean these are acceptable positions but, due to needing to pass through the other profile at a prior point in time to reach this location, navigating toward this position is obviously not an option.

In order to properly account for these cases the matrices for all points in the future are initially combined by using an element-by-element OR operation. In order to develop a single matrix that serves as a master overlap matrix for all points in time. This process is illustrated in Equation 2.

$$\begin{bmatrix} I_{1,1}^{t_1} & I_{1,2}^{t_1} & \cdots & I_{1,N}^{t_1} \\ I_{2,1}^{t_1} & I_{2,2}^{t_1} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ I_{M,1}^{t_1} & \cdots & \cdots & I_{M,N}^{t_1} \end{bmatrix} OR \begin{bmatrix} I_{1,1}^{t_2} & I_{1,2}^{t_2} & \cdots & I_{1,N}^{t_2} \\ I_{2,1}^{t_2} & I_{2,2}^{t_2} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ I_{M,1}^{t_2} & \cdots & \cdots & I_{M,N}^{t_2} \end{bmatrix} OR \ldots$$

$$OR \begin{bmatrix} I_{1,1}^{t_{max}} & I_{1,2}^{t_{max}} & \cdots & I_{1,N}^{t_{max}} \\ I_{2,1}^{t_{max}} & I_{2,2}^{t_{max}} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ I_{M,1}^{t_{max}} & \cdots & \cdots & I_{M,N}^{t_{max}} \end{bmatrix} = \begin{bmatrix} I_{1,1} & I_{1,2} & \cdots & I_{1,N} \\ I_{2,1} & I_{2,2} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ I_{M,1} & \cdots & \cdots & I_{M,N} \end{bmatrix}$$

(Equation 2)

Multi-Vehicle Interactions The case of the subject vehicle interacting with multiple traffic vehicles is considered. In the case of combined interaction with two other vehicles, the master overlap matrix, Equation 2, is initially developed for each subject vehicle – traffic vehicle pair. Once these two matrices are obtained the goal is next to find the OR of all possible combinations of the rows from one matrix with the all of the rows in the other. If the interaction matrix for the subject vehicle with traffic vehicle 1 is noted as $\boldsymbol{I_{S1}}$ and similarly, the interaction matrix for the subject vehicle and traffic vehicle 2 is called $\boldsymbol{I_{S2}}$, each of which has M rows, Equation 3 shows the resulting multi-vehicle interaction matrix. Where, both matrices contain $\boldsymbol{M}$ rows the resulting multi-vehicle interaction matrix will have $\boldsymbol{M^2}$ rows.

$$\begin{bmatrix} I_{S1}(1,:)\ OR\ I_{S2}(1,:) \\ I_{S1}(1,:)\ OR\ I_{S2}(2,:) \\ \vdots \\ I_{S1}(1,:)\ OR\ I_{S2}(M,:) \\ I_{S1}(2,:)\ OR\ I_{S2}(1,:) \\ \vdots \\ I_{S1}(M,:)\ OR\ I_{S2}(M,:) \end{bmatrix}^{N \times M^2}$$

(Equation 3)

More generally the resulting number of rows in the multi-vehicle interaction matrix will be M^V, where V is the number of non-subject vehicles in this analysis. In this case a critical interaction is detected in cases where there exists a row which consists of all Boolean true values. Imminent interactions are also detected similar to prior cases in which all rows only contain true.

Severity Analysis

Purely detecting the presence of critical cases is not sufficient to quantify safety. Based on their nature and current vehicle trajectories it is apparent that all critical cases and non-critical cases are not equal. In order to address this and arrive at a scalar safety metric, methods are currently being developed to quantify risk and severity of these situations. The current state of development of metrics for both critical and non-critical cases is presented in the subsequent sections.

Critical Case Analysis By definition, in a critical interaction the outcome of the scenario is dictated by the actions of the other driver/s. Therefore, the probability of each driver pursuing a certain course of action is directly related to collision probability.

Since all possible positions are computed based upon a set of lateral and longitudinal accelerations, driver behavior is currently being studied to determine if a probability can be associated with each of these acceleration pairs. If the probability of the driver choosing to pursue a set of accelerations resulting in a critical interaction were known, the probability of a collision occurring in that one case is also known. Expanding on this, the probability of a collision occurring for a single vehicle critical interaction may be computed by taking the sum of all independent critical case probabilities.

This method could also be extended to a multiple vehicle case by considering that multi-vehicle critical cases require a certain choice from drivers of each of those vehicles. The collision probability for a single critical case may be computed by finding the products of the probabilities associated with all choices in that case. The total collision probability is then calculated by summing all of the individual critical case probabilities. Bivariate (Ax, Ay) probability distribution functions catered to specific situations and environment are currently being developed and are a topic of ongoing work.

Non-Critical Case Analysis

In the method of analyzing critical cases presented in the prior section, this method carries with it the assumption that all non-critical cases have zero collision probability. In evaluating automated vehicles, this is a conservative approach in that it assumes that an algorithm, if given a choice, will make the correct one. Except, it is known from human driving that, even in cases where a collision is avoidable the necessary path to avoid can require severe action. Based on these observations a severity metric is being developed for non-critical cases.

The inspiration for this method is the desire to extend the concept of deceleration to avoid to two-dimensional interactions. This is done by again considering the elliptic shape of the acceleration map, shown in Figure 4. Calculation of deceleration to avoid for an object can be viewed in this framework as finding the minimum acceleration along the negative longitudinal axis which does not intersect the traffic vehicle if it continues at its current rate. Since vehicle acceleration is limited by the maximum longitudinal deceleration; this quantity could then be normalized by dividing the necessary deceleration by the maximum. This results in a scalar which ranges from zero to one and is a metric of the maneuver severity necessary to avoid a collision.

This process can be extended to two dimensions by computing the length of the vector from the origin to the desired (Ax, Ay) pair and normalizing by dividing by the length of a vector starting from the origin and extending to the ellipse's boundary along the same direction of the original vector. This metric would be computed for all possible avoidance paths and severity would be determined based on the minimum value computed.

This metric is essentially the minimum percentage of vehicle handling authority which would be necessary to avoid all possible collisions. Based on combining this definition with that for critical interactions it can be seen that critical interactions occur in any case where this quantity has a value of one or greater. By combining these two metrics a comprehensive understanding of vehicle interactions is obtained.

SAMPLE CASES

Sample cases have been developed to illustrate the current state of ISM development. Selection of these cases targets scenarios where an analytical solution can be calculated. By verifying the current version of the ISM algorithm in these cases the feasibility of this methodology at least at a basic level is demonstrated. Four of these cases are presented in the following sections. These cases are not intended to provide comprehensive validation of this methodology.

Case#1-Purely Longitudinal Dynamics

The first sample case deals exclusively with longitudinal dynamics. By eliminating any lateral movement of the subject and traffic vehicles, the interaction problem becomes easier to visualize. In this case, the dimensions of both vehicles' possible space goes from 3D (t, X, Y) to 2D (t, X). Also, this case allows for the ISM result to be verified analytically.

There are many methods for determining severity of vehicle interaction for a purely longitudinal case; two approaches are compared with ISM in this document, time to collision (TTC) and deceleration to avoid collision (D2A). The TTC value can be calculated from using Equation 4.

$$TTC = -\frac{\left(X_{t0} - \frac{L_t}{2}\right) - \left(X_{s0} + \frac{L_s}{2}\right)}{V_{t0} - V_{s0}}$$

(Equation 4)

In Equation 4 X_{t0} and X_{s0} are the initial longitudinal position of the traffic and subject vehicles, respectively, V_{t0} and V_{s0} are the initial longitudinal velocities of the traffic and subject vehicles, and L_t and L_s are the length of the traffic and subject vehicles.

The deceleration to avoid can be calculated by knowing that the minimum deceleration occurs when the vehicles are traveling at the same velocity at the point when the distance between them drops to zero. The time at which their velocities are equal,

T_{D2A} is related to the vehicles velocities, V_{t0} and V_{s0}, and, the constant acceleration, $A_{x,s}$ in Equation 5.

$$A_{x,s} = \frac{V_{t0} - V_{s0}}{T_{D2A}}$$

(Equation 5)

The distance between the two vehicles being equal to zero is expressed in Equation 6.

$$\left(X_{s0} + \frac{L_s}{2}\right) + V_{s0} * T_{D2A} + \frac{1}{2}A_{x,s} * {T_{D2A}}^2 = \left(X_{t0} - \frac{L_t}{2}\right) + V_{t0} * T_{D2A}$$

(Equation 6)

By combining Equations 5 and 6, the expression for calculating deceleration to avoid, Equation 7, is derived.

$$A_{x,s} = \frac{(V_{t0} - V_{s0})^2}{2\left(X_{s0} + \frac{L_s}{2} - X_{t0} + \frac{L_t}{2}\right)}$$

(Equation 7)

This equation assumes that the lead traffic vehicle remains traveling at its initial velocity and does not account for the ability of the traffic vehicle to decelerate. The TTC calculation does not account for the acceleration abilities of either vehicle. The newly proposed ISM method however, takes into account both the subject and the traffic vehicles' acceleration capabilities. This allows for the ISM algorithm to calculate the previously defined possible, critical, and imminent interactions.

Due to only needing to address longitudinal dynamics in this case, the onset of critical and imminent interactions can be solved for analytically. The first critical interaction is expected when the profile associated with maximum deceleration of the subject vehicle intersects the profile associated with maximum deceleration of the traffic vehicle. In cases where the subject vehicle acceleration authority is less than or equal to that of the traffic vehicle, and the subject is traveling with a higher initial velocity than the traffic vehicle, a critical interaction will always be present at some point in the future. Therefore, a logical limit must be placed on prediction time. This is consistent with the knowledge that at a certain point in the future all things are avoidable. For this case the prediction time is limited to the time required for the subject vehicle to stop under maximum deceleration.

$$T_{stop} = -\frac{V_x}{A_{x\_min}}$$

(Equation 8)

Based on this decision, critical interactions would occur in a situation where the distance between the two vehicles would be negative before the stop time. This assumes that both vehicles decelerate with their maximum authority. Imminent interaction timing would be calculated where the traffic vehicle accelerates at maximum authority while the subject vehicle applies maximum deceleration. Using the distance formula in Equation 9, the expressions for critical and imminent interactions are defined in Equation 10.

$$D = -\left[\frac{1}{2}A_{x,s} * {T_{stop}}^2 + V_{s0} * T_{stop} + \left(X_{s0} + \frac{L_s}{2}\right)\right] + \frac{1}{2}A_{x,t} * {T_{stop}}^2 + V_{t0} * T_{stop} + \left(X_{t0} - \frac{L_t}{2}\right)$$

(Equation 9)

$$\frac{1}{2}\left(A_{x,t} - A_{x,s}\right) * {T_{stop}}^2 + (V_{t0} - V_{s0}) * T_{stop} - \left(X_{s0} + \frac{L_s}{2}\right) + \left(X_{t0} - \frac{L_t}{2}\right) \leq 0$$

Where $\mathrm{A}_{\mathrm{x,s}} = \mathrm{A}_{\mathrm{x\_min,s}}$ & $\mathrm{A}_{\mathrm{x,t}} = \mathrm{A}_{\mathrm{x\_min,t}} \rightarrow \mathrm{Critical}$

Or $\mathrm{A}_{\mathrm{x,s}} = -\mathrm{A}_{\mathrm{max}}$ & $\mathrm{A}_{\mathrm{x,t}} = \mathrm{A}_{\mathrm{x\_max,t}} \rightarrow \mathrm{Imminent}$

(Equation 10)

To compare these three methods, we begin by comparing the case of two vehicles moving along a straight path. In this case if we assume that both vehicles have a constant velocity then the severity of an interaction is only associated with the distance between the two. Therefore, for any initial relative distance the three severity metrics can be computed and compared. The parameters used in configuring this scenario are in Table 1.

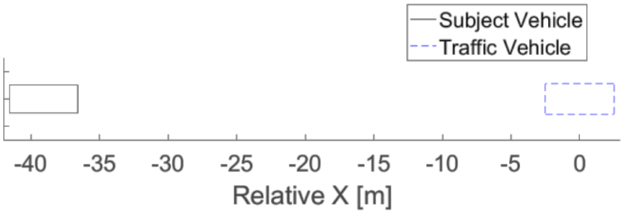
Table 1. Purely longitudinal test case initial conditions

Vehicle	L [m]	V_0 [m/s]	$A_{x,max}$ [m/s^2]	$A_{x,min}$ [m/s^2]
Subject	5	30	7.3	-8.8
Traffic	5	20	7.3	-8.8

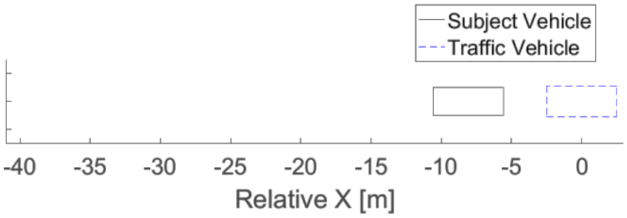
Based on this information a scenario in which the initial distance between the vehicle centers (Δx) was 45 meters is presented. Since the subject vehicle is travelling faster than the traffic vehicle this distance is expected to reduce with time and the points at which each type of interaction occurs can be detected. These results are included in Table 2 and plots of the vehicles at the first critical and imminent locations are shown in Figure 5.

Table 2. Purely longitudinal test case results

Δx (m)	Critical	Imminent	TTC (s)	D2A (m/s^2)
Initial Conditions, T=0				
45	No	No	4.00	-1.25
Detection of Critical Interaction, T=0.591				
39.09	Yes	No	3.41	-1.47
Detection of Imminent Interaction, T=3.691				
8.09	Yes	Yes	0.31	-16.18



(a) First Critical Interaction



(b) First Imminent Interaction

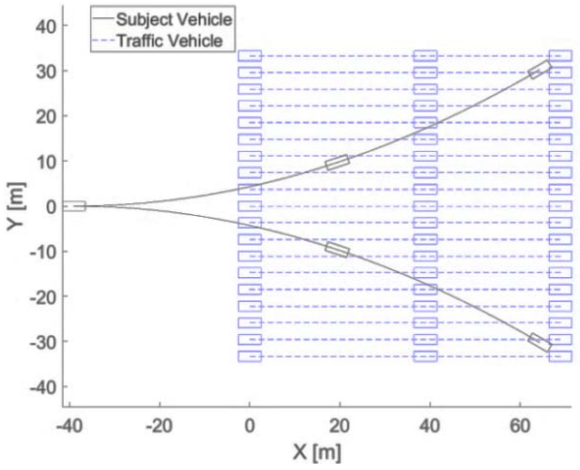
Figure 5. Purely longitudinal single vehicle

The results in Table 2 illustrate the key difference between ISM and other metrics. First the TTC does not provide any direct insight into risk or safety where the ISM is designed to detect risky situations. Next, the deceleration to avoid does not factor in the traffic vehicle's ability to decelerate and therefore can underestimate the possible severity of a situation. By considering the vehicle's possible behavior, situations which may become severe are detected substantially earlier than with other metrics.

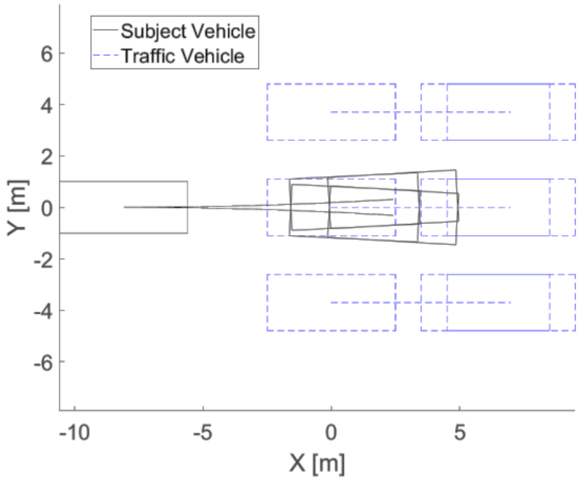
The ISM algorithm determines that a critical case has occurred and that this situation may result in an unavoidable collision when the TTC is still greater than three seconds and the deceleration to avoid the object is less than 0.2 g. The deceleration to avoid is well within the vehicle capability, and the time is fairly large, so this case would not normally be identified as being risky behavior. The ISM detects this cases and once completed could provide the risk associated with the current course of action.

Case #2-Multi-Vehicle Longitudinal Case

The second example case is an extension of the first case. In the first case, the vehicle's lateral acceleration capability was limited. This is a convenient way to simplify the problem, however it is not practical. A scenario can be developed that limits the lateral acceleration capabilities of the subject vehicle by limiting its possible lateral escape routes instead of limiting its lateral acceleration. This can be akin to an infinitely wide car or more practically a row of *k* cars that the subject vehicle cannot pass between or around as shown in Figure 6 and described in Table 3. In all cases, *k* is selected such that the resulting line of vehicles is wide enough to block all paths of lateral escape. Table 4 again shows the TTC and D2A when the first critical and first imminent interactions are detected for the multi-vehicle case. This data shows that the TTC and D2A values in Table 4 agree with those in Table 2. This shows that the multi-vehicle algorithm performance is consistent with the established expectation.



(a) First critical interaction for multi-vehicle (k=19)



(b) First imminent interaction for multi-vehicle (k=3)

Figure 6. Multi-vehicle longitudinal interaction

Table 3. Multi-vehicle longitudinal test case initial conditions

Vehicle	Y_0 [m]	V_0 [m/s]	$A_{y,max/min}$ [m/s^2]	$A_{x,max}$ [m/s^2]	$A_{x,min}$ [m/s^2]
Subject	0	30	±5.1	7.3	-8.8
Traffic	$3.7\left([1:k]-\frac{k+1}{2}\right)$	20	0	7.3	-8.8

Table 4. Multi-vehicle longitudinal test case results

Δx (m)	Critical	Imminent	TTC (s)	D2A (m/s^2)
Initial Conditions, T=0				
45	No	No	4.00	-1.25
Detection of Critical Interaction, T=0.591				
39.09	Yes	No	3.41	-1.47
Detection of Imminent Interaction, T=3.691				
8.09	Yes	Yes	0.31	-16.18

Case #3-Purely Lateral Dynamics

The third sample case is similar to the first, but now we simply deal with only the lateral dynamics, i.e. the vehicles maintain a constant longitudinal velocity. These simplified dynamics still allow for a theoretical calculation of possible interaction time and critical interaction time. Also, due to there being no relative velocity the initial conditions are the same for all real time, therefore, only one real time stamp needs to be analyzed.

Given the initial conditions in Table 5, the ISM predicts the first possible vehicle interaction at a prediction time, $T_{p,}$ of 0.596 s while the theoretical value is 0.591 s. The theoretical value was calculated based on the scenario of both vehicles turning toward each other at their maximum lateral acceleration. This is shown in Figure 7 as the first location where the vehicle’s possible spaces interact. The ISM predicts the critical interaction will happen at T_c=1.025 s with the theoretical value being 1.024 s. This is when the traffic vehicle turns towards the subject vehicle at maximum lateral acceleration and the subject vehicle turns away from the approaching traffic vehicle at maximum lateral acceleration. This critical interaction only occurs because the traffic vehicle has higher lateral acceleration limits than the subject vehicle. This corresponds to the definition of critical interaction previously stated; the driver has no possible escape routes and cedes control of the maneuver outcome. The driver of the subject vehicle can always elect to steer away from the traffic vehicle; therefore, an imminent interaction is not expected in this scenario.

Table 5. Purely lateral test case initial conditions

Vehicle	W [m]	Y_0 [m]	V_0 [m/s]	$A_{y,max/min}$ [m/s^2]	A_x [m/s^2]
Subject	2	0	30	±3.05	0
Traffic	2.2	3.7	30	±6.1	0

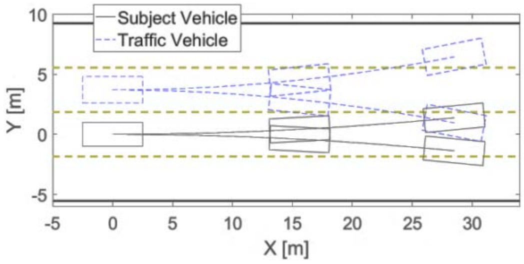


Figure 7. Purely lateral single vehicle

Case #4-Multi-Vehicle Lateral Case

The fourth case takes the same idea presented in Case #2 and applies it to lateral acceleration. Instead of limiting the longitudinal acceleration of a vehicle, a scenario is developed where the longitudinal escape paths of the subject vehicle are limited due to a line of cars in the adjacent lane as shown in Table 6 and Figure 8. The ISM calculates a first possible interaction time of T_p=0.66 s and a critical interaction time of T_c=1.14 s for this maneuver. These values are larger than those in Case #2 because for the first possible interaction, the subject vehicle is allowed to accelerate longitudinally and the traffic vehicle is allowed to decelerate longitudinally resulting in a first possible interaction that is later than in Case #3 where there is no longitudinal acceleration. For the critical interaction, this is larger because both vehicles are decelerating along their curved paths resulting in a longer time before reaching the critical interaction.

Table 6. Multi-vehicle lateral test case initial conditions

Vehicle	X_0 [m]	Y_0 [m]	V_0 [m/s]	$A_{y,max/min}$ [m/s^2]	$A_{x,max}$ [m/s^2]	$A_{x,min}$ [m/s^2]
Subject	0	0	30	±3.05	7.3	-8.8
Traffic1	-9	-3.7	30	±6.1	7.3	-8.8
Traffic2	0	0	30	±6.1	7.3	-8.8
Traffic3	9	3.7	30	±6.1	7.3	-8.8

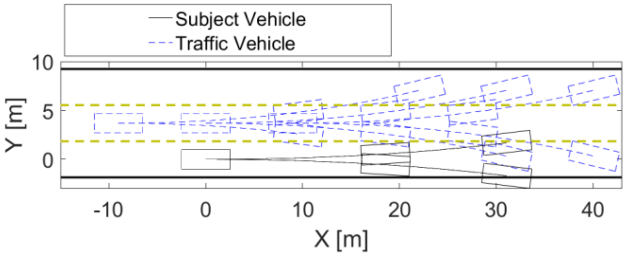


Figure 8. Multi-vehicle lateral interaction

DISCUSSION

The goal of this document is not to provide a comprehensive methodology or extensive validation, but rather to start a conversation. The evaluation and validation of automated vehicles is one of the more substantial and important unresolved questions in this area. Answering this question requires a shift from traditional paradigms of vehicle safety testing to a more comprehensive view of this matter.

The proposed method of safety analysis provides a quantitative window into the predominantly qualitative world of subtle and nuanced traffic interactions. The authors believe that this method and approach provide a sure path toward developing a tool which can be used to quantify automation system performance in simulation, test-track and on-road evaluations.

CONCLUSIONS

This document has introduced the concept of an Instantaneous Safety Metric. The fundamental constructs of its implementation, both geometric region of interest and classification of vehicle interactions have been discussed. Furthermore, the progress in developing an algorithm to implement this method is also presented and discussed. Basic example cases have been used to show some steps toward validation and to present cases of interest which illustrate the importance of using this type of approach.

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