Adjusted Minimum Time-To-Collision(TTC): A Robust Approach to Evaluating Crash Scenarios

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Abstract

Driving simulators provide a unique environment for evaluating critical driving situations where there is a significant possibility of a crash. In these scenarios, a number of dependent measures have been used to evaluate the effect of various treatments or systems. Three such measures are minimum TTC, collisions, and collision velocity but each has inherent problems. When there is a mixture of collision and non-collisions, minimum TTC and collision velocity suffer from a restriction in range that results in a non-normal distribution of data. Collisions are a categorical data source that requires the use of less powerful non-parametric statistics. This paper presents a composite measure that utilizes minimum TTC, collisions, deceleration, and velocity to provide a more robust measure of driver performance in scenarios that result in collisions. This measure, adjusted minimum TTC, indicates how much spare time the driver had or how much sooner the driver should have begun responding to avoid the collision. It is calculated in the same manner as minimum TTC when no collision occurs, but when a collision occurs, adjusted minimum TTC is calculated based on the relative velocity at collision and the deceleration of the driver's vehicle prior to the collision. This paper documents the method for calculating this measure and demonstrates its utility with experimental simulator data.

Introduction

The nature of measurement is that the person doing the measuring strives to find the most accurate method for describing the item being measured. As a carpenter preparing to measure for a cut will select an appropriate tool for the length, so too will a researcher choose a measure that will allow the item being studied to be accurately described. The choice of appropriate measures greatly impacts the effectiveness of the research being conducted, for if the wrong measures are chosen, important differences may go undetected.

Measures of Driving Performance

When conducting driving research where driver performance and response are important, a variety of measures have traditionally been available. General measures of driving performance have tended to concentrate on what the driver does and when the driver does it. These measures have broad appeal because they allow the researcher to understand how systems or treatments impact driver performance. Crash-related measures tend to provide a higher-level assessment of the safety impact of the systems and treatments being evaluated by quantifying the outcome of the event being studied.

General Measures

A variety of general measures have historically been used to evaluate the effects of systems and treatments in the driving environment. These measures include measures of driver response such as throttle, brake, and steering inputs, and driver behaviors such as eye movement and reaction time to events. Driver response measures provide a quantification of the nature and timing of driver response to events. These include such measures as throttle release, mean and maximum deceleration, steering wheel angles, steering instability, etc. This category also includes timing measures such as throttle release and brake application reaction times, as well as categorization measures such as time-to-collision (TTC) at brake application. Although these types of measures provide a wealth of information concerning the nature, magnitude, and timing of the driver’s response, they do so independent of whether the response was successful as far as escaping the situation. To understand that aspect of the response, these measures are combined with crash-related measures.

Crash-Related Measures

Measures related to crash scenarios have taken on particular importance with the increased usage of driving simulation in research. When crashes are examined, it is important to categorize not only the nature of the response but how successful it was. Traditional measurements of collisions—near misses, minimum type I TTC, minimum type II TTC, and crash velocity—have typically been used when evaluating scenarios in which crashes may occur. Minimum TTC and counts of near misses are useful in cases where no crashes occur. Crash velocities are useful in cases where crashes occur, and collision counts are useful when both crashes and avoidances occur. These measures have proved useful to this point, but none provides a powerful unifying measure of event outcomes.

Shortcomings of Standard Crash Measures

Each of the standard crash measures has weaknesses that restrict its utility. Minimum type I and type II TTC provide a continuous measure of how severe a situation resulted from the driver's response to the event so long as the driver does not collide with the other vehicle. For this measure, the larger the TTC, the safer the response. When the driver collides, however, the minimum TTC is zero regardless of whether the driver barely nudges the other vehicle with a small differential velocity or slams into the vehicle with a differential velocity of 70 mph. As a result, minimum TTC experiences a restriction in range, and the distribution of the data becomes non-normal as more crashes occur.

Collision velocity, whether relative velocity or driver velocity, has the same problem as minimum TTC, except that it occurs when crashes do not occur rather than when they do occur. The larger the collision velocity, the worse the situation that resulted from the driver's response. However, when no crash occurs, the collision velocity is zero in all cases regardless of whether the driver stopped a quarter inch behind the vehicle or a quarter mile. As a result, collision velocity experiences a restriction in range, and the distribution of the data becomes non-normal as more non-crashes occur.

Collision and near-miss counts are based on binary classifications of the outcome of the events. As a result, parametric statistics cannot be appropriately used to analyze these measures. Instead, less powerful non-parametric statistics must be used. As a result of the difficulties with all of these measures, it was desirable to develop a parametric measure that could be used both when crashes do and when they do not occur.

Adjusted Minimum Time-To-Collision (TTC)

Adjusted minimum TTC is defined as the amount of "spare time" the driver had based on the avoidance response chosen by the driver. Positive values indicate the amount of extra time the driver had based on the deceleration profile. Negative values indicate how much earlier the driver would have needed to begin the response in order to have avoided the collision.

In the case of no collision, minimum adjusted TTC is the minimum value of type II TTC. When both vehicles are moving and the lead vehicle is decelerating, type II TTC is derived from the following equation of motion assuming continued travel at the current speed by the driver's vehicle:

$$-R = \frac{1}{2} a \times TTC^2 + \dot{R} \times TTC$$

$$\text{where } \begin{cases} R = \text{Range} \\ \dot{R} = \text{ Lead Vehicle Velocity - Following Vehicle Velocity} \\ a = \text{Lead Vehicle Acceleration} \end{cases}$$

TTC is then derived using the quadratic formula as follows:

$$TTC = -\frac{\dot{R} + \sqrt{\left(\dot{R}\right)^2 - (2a)(R)}}{a}$$

Using the same definition of range rate, when the lead vehicle is stationary or travelling at a constant speed, TTC is simply a function of range and range rate expressed as follows:

$$TTC = \frac{R}{-\dot{R}}$$

The above calculations for Minimum Type II TTC would result in a value of zero in the case where a collision occurs. To calculate the adjusted minimum TTC in the case of a crash, the situation preceding the crash is considered. If the lead vehicle is stopped:

$$\text{Adjusted Minimum TTC} = \frac{V_F}{\bar{a}_F}$$

$$\text{where} \begin{cases} V_F = \text{Following Vehicle Velocity at the Time of Collision} \\ \bar{a}_F = \begin{array}{c}\text{Average Acceleration of the Driver's Vehicle} \\ \text{from Brake onset to collision}\end{array} \end{cases}$$

If the lead vehicle is moving and the following vehicle is decelerating as quickly as the lead vehicle or greater:

$$\text{Adjusted Minimum TTC} = \frac{V_F - V_L}{\bar{a}_F - \bar{a}_L}$$

$$\text{where} \begin{cases} V_F = \text{Following Vehicle Velocity at the Time of Collision} \\ V_L = \text{Lead Vehicle Velocity at the Time of Collision} \\ \bar{a}_F = \begin{array}{c}\text{Average Acceleration of the Driver's Vehicle} \\ \text{from Brake onset to collision}\end{array} \\ \bar{a}_L = \begin{array}{c}\text{Average Acceleration of the Lead Vehicle} \\ \text{from Brake onset to collision}\end{array} \end{cases}$$

By definition, if the lead vehicle is moving and the following vehicle is not decelerating as quickly as the lead vehicle, the driver could not have avoided the collision based on the current response, and:

$$\text{Adjusted Minimum TTC} = -\infty$$

Thesis

For the evaluation of driving scenarios in which collisions are likely, the use of the composite measure of adjusted minimum TTC provides a more robust measure of driving performance that does not have the restriction in range associated with minimum TTC and collision velocity nor the lack of power associated with collision outcome data.

To demonstrate these differences in effectiveness, driver simulation data for a scenario that has a mixture of crash and non-crash responses has been evaluated. The simulation utilized a model of the driver that would react to information in the driving environment in order to make appropriate adjustments to the vehicle's velocity. Additional details concerning the model can be found in Brown, Lee & McGehee (2001a, 2001b). The model was used to generate data that examined changes in assumed reaction times and decelerations for a rear-end collision warning algorithm. Additional details concerning the algorithms can be found in Burgett et al. (1998) and Lee et al. (2002). The conditions examined were the combinations of assumed deceleration levels of 0.4 and 0.75 g, and reaction times of 1.25 and 1.50 s. Table 1 details the assignment to condition. As the particular effects associated with these independent measures is not the focus of this paper, these combinations of assumed deceleration and assumed reaction time will be referred to by condition number throughout the reminder of the paper.

Table 1. Condition Definition.

Condition	Assumed Deceleration (g)	Assumed Reaction Time (s)
17	0.4	1.25
24	0.75	1.25
29	0.4	1.5
36	0.75	1.5

Using data from this analysis, the applicable dependent measures were calculated. A univariate analysis of the measures was performed to allow for an examination of the normality of the data and to examine any restrictions in range. Additionally, a simple experimental comparison is demonstrated to show the effect on the analyses of the experimental conditions.

Findings

Distribution of Parametric Data

Due to space constraints, the comparison of the form of the data with regard to restriction in range and normality will be limited to two conditions, namely two different assumed decelerations with an assumed reaction time of 1.25 s. Figure 1 shows the normal probability plots for two conditions for minimum type II TTC, relative velocity at collision, and adjusted minimum TTC. When comparing the distributions of data for the three measures under consideration, condition 17 will first be considered. It should be noted for this condition that two collisions occurred during these drives. By examining the first row of plots in Figure 1, the similarities between minimum type II TTC and adjusted minimum TTC are evident, as the only two data points that differ are the two collision data points. Due to only two collisions, the restriction in range has little effect for minimum type II TTC; however, relative velocity at collision is severely hampered by this restriction in range with only two non-zero data points.

For condition 24, 15 crash and 15 non-crash situations were observed. The second row of Figure 1 illustrates the impact of this distribution of crashes on minimum type II TTC, relative velocity at collision, and adjusted minimum TTC. As can be seen from the figure, both minimum type II TTC and relative velocity at collision suffer from significant effects of the restriction in range, whereas adjusted minimum TTC has no restriction in range and is for the most part normally distributed. It is clear from examining Figure 1 that the restriction in range results in a non-normal distribution for each of these measures for this condition that will result in difficulties in using parametric statistics to examine them.

Non-Parametric Measure: Crashes

The issue with non-parametric measures such as crashes is that they require the use of less powerful non-parametric statistics. For binary/categorical data, the appropriate test is the chi-square test. Although these tests have little difficulty detecting obvious and large differences, they may miss more subtle differences.

Statistical Findings

Collisions

The distribution of crashes and non-crashes is shown in Table 2. The overall analysis of crashes shows that there are significant differences between conditions ($\chi^2 = 22.79$, 3, $p < 0.0001$). When examining the pair-wise comparisons, significant differences are found between condition 24 and conditions 17 or 29 ($\chi^2 = 19.12$, 1, $p < 0.0001$), and between condition 24 and condition 36 ($\chi^2 = 15.49$, 1, $p = 0.0001$. No statistical difference was found between condition 36 and conditions 17 or 29 ($\chi^2 = 3.66$, 1, $p = 0.0556$).

Table 2 Crashes by condition

	Condition			
	17	**24**	**29**	**36**
Crashes	2	15	2	6
Noncrashes	28	15	28	24

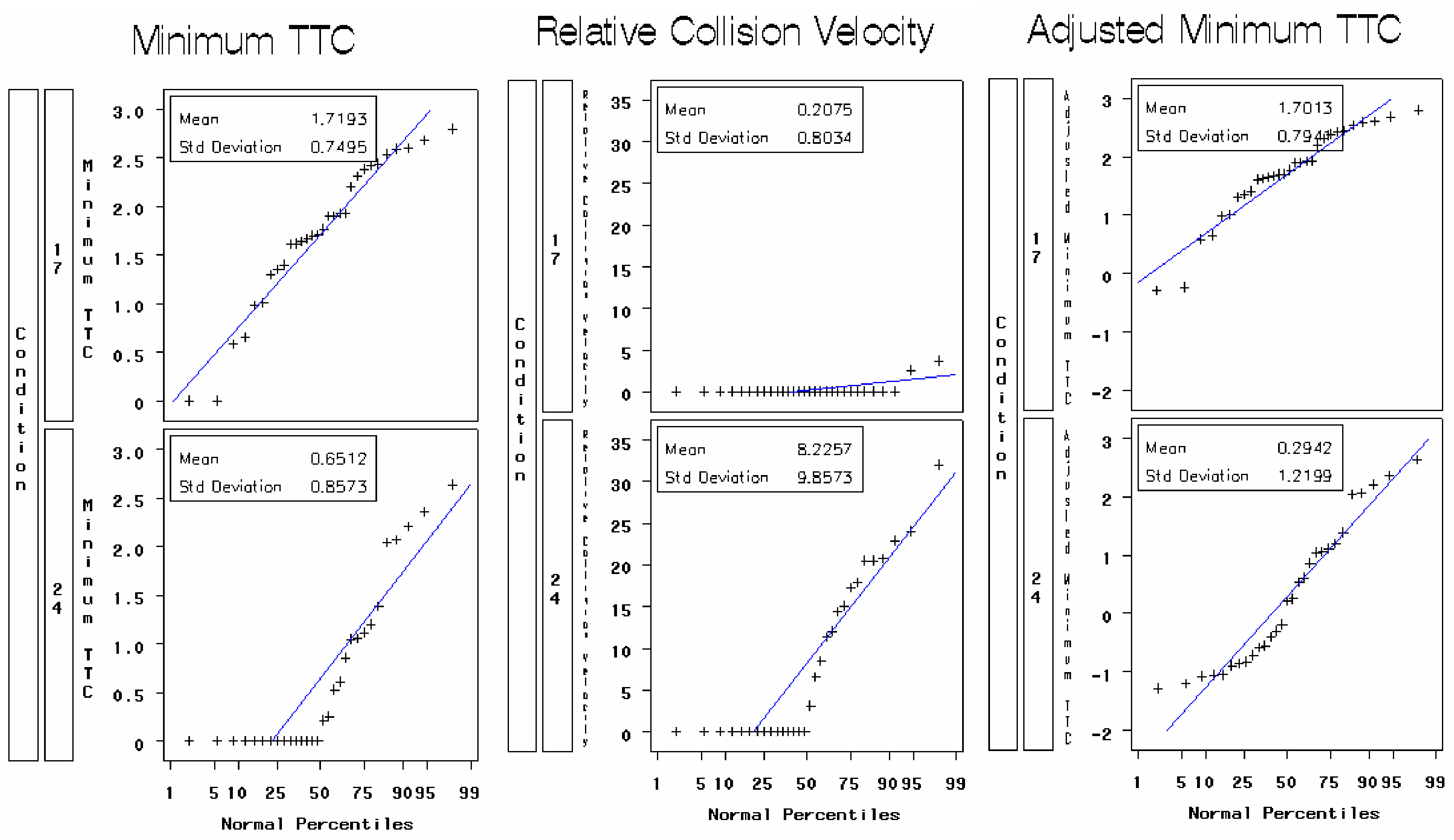

Figure 1. Normal probability plots for the two conditions examined
Condition 17 is an assumed deceleration of 0.4 g and condition 24 is 0.75 g
a) Minimum Type II TTC b) Relative Velocity at Collision c) Adjusted Minimum TTC

Minimum Type II TTC, Relative Velocity at Collision, and Adjusted Minimum TTC

For these analyses, the SAS General Linear Models (GLM) procedure was used to analyze the effect of condition on the measures. The Tukey posthoc test was used to determine differences between the different conditions. For Minimum Type II TTC, collision velocity, and adjusted minimum TTC, significant main effect differences for condition were found for each of the measures ($p < 0.0001$ for each). For Minimum Type II TTC, the Tukey posthoc test revealed that significant differences were present between conditions 24 and 36 and conditions 17 and 29. For relative velocity at collision, the Tukey posthoc test revealed differences between condition 24 and conditions 17, 29, and 36. For adjusted minimum TTC, the Tukey posthoc test revealed differences between conditions 24 and 36 and conditions 17, and 29. Figure 2 illustrates the differences between the four conditions.

Discussion

When the distribution of the data was examined, it was clear for the two conditions examined that crash velocity suffers significantly from restriction in range, particularly when few drivers avoid collisions; whereas minimum type II TTC suffers the same problem when there are few crashes. When there is an approximately equal distribution of crashes and non-crashes, both minimum type II TTC and relative velocity at collision suffer from this problem. Although this problem can often be overcome, the resulting nonnormality does present challenges for using parametric statistics. Crashes are less sensitive than the parametric measures discussed and require the use of less powerful statistics. The example given provided obvious differences that were easily identified; however, smaller differences in crash rates and other subtle differences are difficult to tease out with this measure.

As discussed earlier, adjusted minimum TTC provides a combination measure that includes minimum type II TTC, crashes, and relative velocity at collision. As a result, adjusted minimum TTC does not suffer from the inherent limitations in range that are present in relative velocity at collision and minimum type II TTC, and the data tend to be more normally distributed than either of the other measures which makes the use of parametric statistics much more straightforward.

Overall, adjusted minimum TTC provides another measure to the researcher’s arsenal that is more robust than either relative velocity at collision or minimum type II TTC in that it provides good data concerning the outcome of the events that is not subject to restriction in range. Nothing is lost from minimum type II TTC in that if no collisions occur, adjusted minimum TTC provides the same data set; however, when collisions do occur it allows the researcher to distinguish the relative severity of the crashes that would have otherwise been coded as minimum type II TTCs of zero seconds. Adjusted minimum TTC also takes into account all of the information from relative collision velocity. As a result, this measure proves useful when examining events in which a number of crash and non-crash outcomes are likely to be observed.

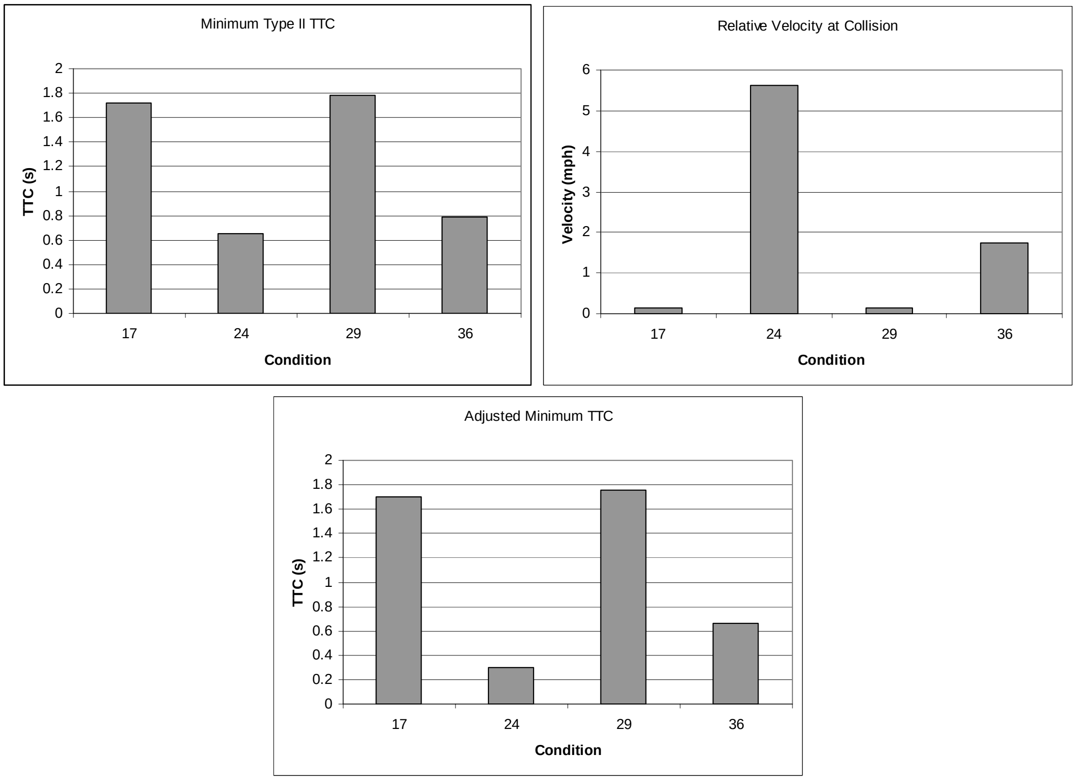

Figure 2 Plots of means by condition for minimum type II TTC, Relative Velocity at Collision, and adjusted minimum TTC

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