A General Measure of Collision Hazard in Traffic

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Abstract

A collision hazard measure that has the essential characteristics to provide a measurement of safety that will be useful to AV developers, traffic infrastructure developers and managers, regulators and the public is introduced here. The Streetscope Collision Hazard Measure (SHM™) overcomes the limitations of existing measures, and provides an independent leading indication of safety.

- Trailing indicators, such as collision statistics, incur pain and loss on society, and are not an ethically acceptable approach.
- Near-misses have been shown to be effective predictors of the likelihood and severity of incidents.
- Time-to-Collision (TTC) provides ambiguous indication of collision hazards, and requires assumptions about vehicle behavior.
- Responsibility-Sensitive Safety (RSS), because of its reliance on rules for individual circumstances, will not scale up to handle the complexities of traffic.
- Instantaneous Safety Metric (ISM) relies on probabilistic predictions of behaviors to categorize events (possible, imminent, critical), and does not provide a quantitative measure of the severity of the hazard.
- Inertial Measurement Unit (IMU) acceleration data is not correlated with hazard or risk.
- A new measure, based on the concept of near-misses, that incorporates both proximity (separation distance) and motion (relative speed) is introduced.

The new measure presented here gathers movement data about vehicles continuously and a quantitative score reflecting the hazard encountered or created is computed nearly continuously, from which the riskiness or safeness of the behavior of vehicles can be determined.
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1 Introduction

1.1 Motivation and Objectives

Measurements of traffic safety and risk have been proposed since at least John Hayward’s introduction of Time-to-Collision (TTC) in 1972. [3] Since that time, a variety of additional traffic safety measures have been proposed and used, including both leading and trailing indicators. [4] This paper introduces a novel leading measure of collision hazards in traffic that overcomes difficulties with prior measures, and is quantitative, objective, continuous, and general.

Measuring and assessing the safe operation of vehicles in traffic is essential to the deployment of automated mobility, as well as improving traffic safety for conventional human-operated vehicles. Existing approaches lack key characteristics that will be required by regulators and the public.

Trailing or lagging indicators of traffic safety are important benchmarks, however, they are problematical for assessing the risk and safety of new systems, either roadways, traffic controls, or vehicles. This is precisely because they require the accumulation of collision statistics, and necessarily therefore require collisions to occur. Traffic collisions incur property damage, injuries, and death and the ethical problems of inflicting pain and loss on society (in the process of determining the safety of an AV system) are unacceptable.

Therefore, for the introduction of new systems, particularly automated vehicles, leading indicators of traffic risk and safety must be used. Existing leading road safety indicators have limitations and/or shortcomings, and a new general measure is needed. A summary of the most critical shortcomings of several of the most commonly used measured is presented below.

Importantly, a general quantitative measure of traffic safety and risk must treat each traffic object (vehicle, pedestrian, bicyclist, etc.) as a “black box”, meaning that only the external behavior of the object can be utilized in computing the measure. This is identical to the conditions of an on-road driving test, where the evaluator simply observes the actions (behaviors) of the vehicle as it is being driven, and is not engaged in a dialog with the driver about what he sees nor what considerations he is making regarding control actions. The new measure introduced here is such a “black box” observational measure.

A future publication will present initial results demonstrating correlation of the new measure with historical collision data, providing validation that the new measure is useful in predicting likelihood (frequency of occurrence) and severity of collisions.

1.2 Existing Methods

A number of existing approaches to determining traffic safety are summarized here.

1.2.1 Near-Misses

Hayward suggested that near-misses could be an effective leading indicator of traffic risk and safety:

NEAR-MISS traffic events have been considered for use as predictors of accident rate characteristics at roadway locations. The near miss, loosely defined, is a traffic event that produces more than an ordinary amount of danger to the drivers and passengers
involved. Near misses would appear to be closely related to the accident pattern witnessed at a location and, therefore, could become an attractive alternative measure to accident-based safety determination. [3, page 24]

Other fields have utilized near-misses as leading indicators of risk for some time [5, 6, 7], including civil aviation since at least 1958:

The Aviation Safety Reporting System, or ASRS, is the US Federal Aviation Administration’s (FAA) voluntary confidential reporting system that allows pilots and other aviation professionals to confidentially report near misses or close call events in the interest of improving aviation safety. [8]

The chemical processing industry has also implemented near-miss management systems.

In review of adverse incidents in the [chemical] process industries, it is observed, and has become accepted, that for every serious accident, a larger number of incidents result in limited impact and an even larger number of incidents result in no loss or damage.

Despite their limited impact, near misses provide insight into accidents that could happen. [9, page 445]

“Near-crash” events were explored in the 2006 DOT/NHTSA 100-Car Naturalistic Driving Study:

- **Near-Crash**: Any circumstance that requires a rapid, evasive maneuver by the subject vehicle, or by any other vehicle, pedestrian, cyclist, or animal, to avoid a crash. A rapid, evasive maneuver is defined as steering, braking, accelerating, or any combination of control inputs that approaches the limits of the vehicle capabilities. As a guide, a subject vehicle braking greater than 0.5 g or steering input that results in a lateral acceleration greater than 0.4 g to avoid a crash, constitutes a rapid maneuver.

As shown, while these criteria were based somewhat upon quantitative kinematic criteria, they were subjective in nature. While such definitions were useful for purposes such as classifying video data, they were not useful for precisely defining events or as criteria for other purposes, such as warning algorithms. [10, Page 139]

Despite the limitations of defining and detecting “near-crash” events, the study identified roughly 30 times as many “near-crashes” as crash events. [10, Page 141] The study also identified, particularly in the many scatter plots of measured data, the serious problems that arise from computations of traffic characteristics (e.g., TTC and IMU) that are not monotonic: more severe traffic hazards do not always result in a value that reflects a greater degree of hazard or risk than less severe hazards.

The majority of near-miss reporting systems rely on observer judgment as to whether a near-miss occurred or not, and at most have an informal qualitative assessment of severity. These approaches are not suitable for determination of traffic risk and safety because of the wide range of degree or severity of near-misses in traffic; everything from inconsequential movement at large
distances and low relative speeds to inches of separation at high speed. Systems and approaches that count the occurrence of near misses, as binary events, are not useful for vehicular traffic. The collision hazard measure introduced here utilizes the concept of near-misses among traffic objects (vehicles, pedestrians, bicycles, stationary objects), and defines a quantitative and continuous measure of hazard or degree of near-miss.

1.2.2 Historical Collision Statistics

A common practice is to measure the safety of the behavior of a vehicle on the basis of the frequency of occurrence of collisions. Typical collision occurrence data is shown in Table 1.

Table 1: Rates of involvement in all police-reported crashes, injury crashes, and fatal crashes per 100 million miles driven in relation to driver age, United States, 2014-2015. [11]

| Age of Driver | All Crashes | Injury Crashes | Fatal Crashes |
|---------------|-------------|----------------|---------------|
| 16-17         | 1,432       | 361            | 3.75          |
| 18-19         | 730         | 197            | 2.47          |
| 20-24         | 572         | 157            | 2.15          |
| 25-29         | 526         | 150            | 1.99          |
| 30-39         | 328         | 92             | 1.20          |
| 40-49         | 314         | 90             | 1.12          |
| 50-59         | 315         | 88             | 1.25          |
| 60-69         | 241         | 67             | 1.04          |
| 70-79         | 301         | 86             | 1.79          |
| 80+           | 432         | 131            | 3.85          |

Some drivers make less safe decisions (and take less safe actions) than others, however, the infrequency of collisions, and the many contributing factors beyond driver decision-making to the occurrence of collisions, render historical collision statistics of limited use to evaluate driver performance, or to judge whether a driver (automated or human) is sufficiently safe to drive, particularly in congested and complex scenarios.

1.2.3 Time-to-Collision (TTC)

Some practitioners in the field of traffic safety use an estimate of time-to-collision or TTC to indicate whether the vehicle being analyzed is in a condition of high likelihood of an impending collision.

Hayward defined time to collision as follows:

[T]he measure is the time required for two vehicles to collide if they continue at their present speeds and on the same path. [3, page 27]

This measure has significant limitations, particularly in that the time until a collision will occur is highly dependent on the speed of the vehicle, the movements of the object with which it might collide, and the road conditions, none of which are incorporated into the time-to-collision measure.[12]

Brown noted a particular type of problem with TTC.
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. [12, page 42]

van der Horst identified one of the key limitations of TTC.

[T]he relationship between TTC_{\text{min}} and conflict severity scores is not unambiguous; severe conflicts have a low TTC_{\text{min}}, but not all conflicts with a low TTC_{\text{min}} are regarded as severe. [13, page 107]

A higher-hazard encounter, e.g., one that has the potential to result in a collision with high relative speed (and therefore would produce significant damage and/or injury) can have a larger (and therefore apparently less concerning) TTC than a lower-hazard encounter, such as one where the potential collision would occur with nearly zero relative speed. This example illustrates that TTC is not monotonic with hazard and risk, as will be discussed further below.

Many attempts to improve TTC have been made, principally focusing on assumed behavior (e.g., deceleration) of the following vehicle.

Time to collision is an important time-based safety indicator for detecting rear-end conflicts in traffic safety evaluations. A major weakness of the time to collision notion is the assumption of constant velocities during the course of an accident.

... Results indicate that in the third case (linear acceleration), the average duration of exposure to critical time to collision values is greater than the others. So, applying time to collision based on the assumption of linear acceleration in collision avoidance systems would decrease driver errors more than other cases. [14, page 294]

These limitations render TTC unsuitable as a general measure of collision risk in traffic.

1.2.4 Responsibility-Sensitive Safety (RSS)

Responsibility-Sensitive Safety (RSS) is a set of five rules intended to ensure that automated vehicles operate safely. [15] These are all sensible rules, however, the full complexity of driving simply cannot be captured in five rules.¹

01. Safe Distance Enforce a safe following distance from a vehicle ahead, based on vehicle speed and stopping ability.

02. Cutting In Merge into a lane with sufficient lateral distance from other vehicles.

03. Right of Way Give right of way to other vehicles.

04. Limited Visibility Be cautious in areas of limited visibility.

¹https://www.mobileye.com/responsibility-sensitive-safety/
05. Avoid Collisions  

If an object suddenly appears in the AV’s direct path, the AV must avert a crash by veering into the next lane, provided it would not cause a different collision.

While the first two rules include a quantitative measurement of $d_{\text{min}}$, which is defined as the minimum safe distance for those two maneuvers, RSS does not provide any sort of quantitative measurement of vehicle safety in traffic. The first two are behavioral rules that are to be observed, rather than a quantitative measure of how safely a vehicle is behaving. The remaining three rules are important, but informal and not quantitative, and provide no utility in measuring the safety of the operation of a vehicle. Instead, RSS is a set of guidelines for automated vehicle control decision-making.

Methods that utilize rules for particular maneuvers or situations, such as RSS, will not scale well to even a portion of the full range of traffic scenarios encountered in real traffic, because of the large number of rules required to accommodate each different type of maneuver.

Rules 3, 4, and 5 assume that vehicle controllers will behave accordingly, and will have the capability to do so.

A continuous quantitative measure of collision hazards in traffic, such as the one introduced here, can assess the risk and safety of a vehicle being operated in accordance with the RSS rules.

1.2.5 Instantaneous Safety Metric (ISM)

Instantaneous Safety Metric (ISM), developed by the U.S. National Highway Traffic Safety Administration [16], predicts all future positions of one or more vehicles, and examines the overlap of future reachable regions to determine whether there is a “critical” or “imminent” overlap of regions. An extended approach (Model Predictive Instantaneous Safety Metric or MPrISM) is presented in [17].

To determine whether a future interaction is “critical” or “imminent” requires the determination of “the probability of the driver choosing to pursue a set of accelerations” [16, page 6], in other words, a prediction of the actions of the operator of each vehicle is required.

Importantly, the results of computing the future reachable regions and the possible regions of overlap is one of the four outcomes listed below.

There are four possible combinations resulting from interaction between the possible and unavoidable spaces of two vehicles (Vehicles A & B in this case). [18, page 20]

1. The possible space of both vehicles overlap. (Possible Interaction)
2. The unavoidable spaces of both vehicles overlap. (Imminent Interaction)
3. The unavoidable space of Vehicle A overlaps the possible space of Vehicle B. (Critical interaction for Vehicle A)
4. The possible space of Vehicle A overlaps the unavoidable space of Vehicle B. (Critical Interaction for Vehicle B)

This is not a quantitative measure of risk of collision; it is a categorical indicator rather than a metric. The ISM can determine whether it is possible for an “interaction” to occur in the future, but other than identifying the future interaction as being either “possible”, “imminent”, or “critical”, the ISM provides no quantitative indication of the degree of risk nor the severity of the potential consequences.
1.3 Disengagements

The number of disengagements of the onboard decision-making system per mile (where a disengagement is a manual override of the automated system, such as described in California, California Code of Regulations, Title 13, Div. 1, Ch. 1, Article 3.8, §227.50) is also used as an indication of the performance and safety of the behavior of a vehicle.

The key assumption is that “disengagements” occur when hazardous driving conditions are encountered that the controller does not handle safely.

The number of “disengagements” per mile is not a useful measure of the behavior or safety or risk of an automated vehicle. “Disengagements” can have many causes which may not be related to the behavior or decision-making system of the vehicle, they are not repeatable, are subject to the judgment of the safety driver and therefore occur due to subjective considerations and as a result are not objective, and are influenced by the selection of the conditions and scenarios under which the vehicle is operated and the operational policy or policies under which the driver operates. [19]

As a result, disengagement rate is not an effective measure of the hazards encountered by an automated vehicle, and is at best an indirect indicator of operational risk and safety.

1.4 Inertial Measurement Unit (IMU)

A number of current approaches to measuring risk and safety of vehicles utilize data from an onboard inertial measurement unit (IMU). This data can indicate rapid deceleration (“hard braking”) or rapidly executed turns (“swerving”), and it is thought that events of this type, with accelerations above a threshold, reflect unsafe operation of the subject vehicle.

While IMU data is readily available, either from onboard accelerometers or from onboard electronics such as mobile phones, smooth driving (i.e., with consistently low levels of acceleration) are at best a poor proxy for the risk or safety of the operation of a vehicle, for two important reasons:

1. IMU data is blind to other traffic objects, and therefore necessarily takes no account of how the subject vehicle is moving in relation to these other traffic objects. As a result, IMU data reflects nothing about how the subject vehicle is interacting with traffic.

2. Many cases have demonstrated events where a vehicle was smoothly driven into a collision. Similarly, hard braking occurs when a skilled driver avoids a collision, for example in the classic example of a child chasing a ball into a lane of traffic from between two parked cars.

The use of IMU data relies on the assumption that rapid decelerations are related to risky driving behaviors. The lack of correlation of IMU data with risk and safety of the operation of a vehicle makes it unsuitable for use as a measure.

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2 13 CCR §227.50: For the purposes of this section, “disengagement” means a deactivation of the autonomous mode when a failure of the autonomous technology is detected or when the safe operation of the vehicle requires that the autonomous vehicle test driver disengage the autonomous mode and take immediate manual control of the vehicle, or in the case of driverless vehicles, when the safety of the vehicle, the occupants of the vehicle, or the public requires that the autonomous technology be deactivated. (b) Every manufacturer authorized under this article to test autonomous vehicles on public roads shall prepare and submit to the department an annual report summarizing the information compiled pursuant to subsection (a) by January 1st, of each year.
1.5 Definitions

Subject Vehicle is the vehicle whose behavior, safety and risk are being analyzed.

Traffic Objects are other vehicles, pedestrians, bicyclists, and other moving objects in a traffic scenario. In any particular traffic scenario there will be $N$ traffic objects (in addition to the subject vehicle). Each traffic object is identified by a number from 1 to $N$.

Traffic Scenario is a physical arrangement of roads and/or streets including traffic controls, street markings, curbs, crosswalks, and traffic objects. A typical traffic scenario may last 15-30 seconds.

Near-Miss is a circumstance where the subject vehicle moves at some distance from a traffic object at some speed in relation to the traffic object, but a collision does not occur.

Position $\vec{p}$ is the vector position of the subject vehicle ($\vec{p}_v$) and each traffic object ($\vec{p}_{oi}$).

Separation Distance $d_{sep}$ is the nearest distance between the subject vehicle and a traffic object, as shown in Equation 1 and illustrated in Figures 1 and 2.

$$d_{sep} = |(\vec{p}_{oi} - \vec{p}_v)|$$

Separation Distance $d_{sep}$ could also be a distance between representative points or locations on the subject vehicle and a traffic object, such as the center point of a bounding box or quadrilateral enclosing or representing the vehicle or object.

Separation Distance unit vector $\vec{u}_{d_{sep}}$ is the unit vector in the direction of $d_{sep}$ as shown in Equation 2.

Velocity $\vec{v}$ is the vector velocity of the subject vehicle ($\vec{v}_v$) and each traffic object ($\vec{v}_{oi}$).

Relative Speed $S_{rel}$ is the relative scalar speed of the subject vehicle in relation to a traffic object, as shown in Equation 5 and illustrated in Figures 1 and 2.

$$u_{d_{sep}} = \frac{(p_{oi} - p_v)}{|p_{oi} - p_v|}$$

$$S_v = (\vec{v}_v \cdot (\vec{p}_{oi} - \vec{p}_v)) \times \vec{u}_{d_{sep}}$$

$$S_{oi} = (\vec{v}_{oi} \cdot (\vec{p}_{oi} - \vec{p}_v)) \times \vec{u}_{d_{sep}}$$

$$S_{rel} = \left| \vec{S}_v - \vec{S}_{oi} \right|$$

if $S_{rel} > 0$; separating/diverging

if $S_{rel} < 0$; approaching/converging

Grip is the maximum safe acceleration that the subject vehicle can exhibit. The measure uses both braking grip and lateral grip to incorporate the different capabilities of the subject vehicle to brake and steer. Note that grip will be reduced by slippery road or street conditions.

Lateral Acceleration $a_{lat}$ is the lateral acceleration exhibited by the subject vehicle or a traffic object when turning.
Figure 1: Separation Distance ($d_{sep}$) and Relative Speed components ($\vec{S}_v$ and $\vec{S}_{o_i}$) between the Subject Vehicle moving with velocity $v_v$ and Traffic Object $i$ moving with velocity $v_{o_i}$. 
Figure 2: Relative Speed \( (S_{rel}) \) between the Subject Vehicle moving with velocity \( \vec{v}_v \) and Traffic Object, moving with velocity \( \vec{v}_{oi} \).
**Minimum Turning Radius**  
$r_{t_{\text{min}}}$ is the minimum radius of a turn that can be executed by the subject vehicle or a traffic object. $r_{t_{\text{min}}}$ is subject to *grip* and is an indication of the maneuverability of the subject vehicle and each traffic object.

**Pair-wise** is the successive consideration of the movement of the subject vehicle with each traffic object.

**Disengagement** is a manual override of the automated system. See section 1.3.
1.6 Approach

The novel Streetscope collision hazard measure (SHM™) introduced here provides a method to quantitatively determine the varying levels of hazard encountered and created by the operation of a vehicle, and as a result, estimates of safety and risk. Unlike existing assessments of vehicle safety that pertain to the ability of the subject vehicle to protect its occupants after a collision begins, this measure assesses the performance of vehicles prior to and entirely without reference to collisions. Collision data is customarily gathered and assessed as a frequency of occurrence and severity of outcome. Collisions among existing passenger vehicles are relatively infrequent (from a statistical standpoint), limiting the analytic and predictive power of collision occurrence data.

In contrast, the new measure presented here gathers movement data about vehicles continuously and a quantitative score reflecting the hazard encountered or created (from which the riskiness or safeness of the behavior of vehicles can be estimated) is computed nearly continuously, limited only by the rate at which the sensors provide updated measurements of the positions and velocities of vehicles and road conditions.

The new measure is based on the concept of near-misses, rather than collisions. The concept of a near-miss comprises two kinematic elements: proximity (near) and motion (miss). The new measure incorporates both proximity (separation distance) and motion (relative speed).

In a near-miss a subject vehicle passes other traffic objects (i.e., vehicles, pedestrians, bicyclists, any moving or stationary object in a traffic scenario) but does not collide. The new measure is based, in part, on the proximity of the vehicle to each traffic object and the relative speed between the vehicle and each traffic object. In this way, the new measure can assess how near a vehicle is to a collision with another traffic object, and the relative speed. A small distance and low speed can be equivalent to a higher speed at a larger distance.

Other factors contribute to the degree or severity of a near-miss. The maneuverability of each traffic object plays an important role, since traffic objects have limits on their ability to change speed and direction. If the road/street surface is slippery, the reduced grip reduces the control authority of each traffic object, increasing the hazard.

Therefore, a measure \( m \) of collision hazard between each pair of traffic objects should be a function \( f \) of the following four quantities:

1. The position \( \vec{p} \) of each traffic object
2. The velocity \( \vec{v} \) of each traffic object
3. The maneuverability \( r \) of each traffic object (an estimate of the ability to turn and stop)
4. The grip or the coefficient of friction between traffic objects and the street/road

\[
m = f(\vec{p}, \vec{v}, r, \text{grip})
\]  

(8)

Because the new measure is computed nearly continuously for the subject vehicle and each traffic object, an aggregation of the data into a score is performed. One such aggregation is an accumulation of the hazard measure data into a histogram where the number of times a hazard value is determined for each value of the hazard value are accumulated and displayed in a bar-chart. This results in a chart, similar to the one shown in Figure 3, of frequency-of-occurrence vs. degree of near-miss.
While a histogram (as with any aggregation of data) does not fully capture the behavior of a vehicle in a complex traffic scenario, it represents the key characteristics that can be compared.

Importantly, for validation purposes, historical collision data can also be plotted in a histogram, showing the number of times a collision of a particular severity occurs for each value of severity.

Experience with near-miss data has shown that, in aggregate, they are predictive of the likelihood and severity of incidents. [7, 9, 20, 21, 22]

The new measure can be used for evaluation of the performance of an automated vehicle, in particular the performance of the sensors on the vehicle, the configuration of the sensors on the vehicle, and the decision-making performed by the vehicle. While the measure is intended to be applied to automated vehicles, it can equally be used to provide a score for human drivers (and, in-effect, their sensors and decision-making).

The measure can be computed from vehicle and traffic object data (positions and velocities) that are generated by sensors onboard one or more vehicles, either moving or stationary, or generated by stationary sensors, such as video cameras used for traffic management.

No such driver behavior score or measure exists today, other than the trailing/lagging indicator: frequency of occurrence of collisions, and the indicators such as those derived from IMU data briefly reviewed above.
Figure 3: An example histogram of values of the collision hazard measure.
2 Method

2.1 Characteristics

The key characteristics of any effective collision hazard measure include:

1. **Leading:** The measure determines hazards prior to the occurrence of collisions, in contrast to collision statistics that determine hazards after a number of collisions have occurred.

2. **Quantitative:** The result of the computation of the measure is a numerical representation of the collision hazard encountered.

3. **Continuous:** The quantitative result is on a continuous scale, e.g., from 0 (safe) to 100 (a few centimeters from collision), and is nearly continuous in time, subject only to the update rate of the traffic sensor(s) used.

4. **Independent:** The computation of the measure relies only on external observation of vehicles and traffic objects, and road/street surface conditions, and not on sensor data or decision-making involved in the control of the vehicle. The measure considers each traffic object to be a “black box”, not subject to internal scrutiny.

5. **Direct:** The measure directly determines the hazard between traffic objects, rather than indirect or proxies for hazard.

6. **Repeateable:** Observation of the same behavior in the same traffic scenario will produce the same quantitative value of the collision hazard measure.

7. **No Assumptions:** The measure does not make use of assumptions or predictions about the actions or behaviors of traffic objects.

8. **Monotonic:** A more severe collision hazard will always result in a larger value of the collision hazard measure. Two identical collision hazards, generated by different traffic conditions, will always result in the same value of the collision hazard measure. To be at all useful, the measure should at least conform with the properties of an *Ordinal Scale*, preferably a *Ratio Scale* [23, 24] summarized in Appendix A on Page 22.

9. **Objective:** No qualitative or subjective input is included in the computation of the result. The result depends solely on the measured kinematics of the vehicles and traffic objects, and road/street surface conditions.

10. **Computable:** Given the kinematics (positions and velocities) of the subject vehicle and other traffic objects in a scenario, and estimates of the capabilities of the subject vehicle to stop and turn, the measure can be automatically calculated by a machine such as a computer.

11. **Scalable:** The computation of the measure does not depend on the complexity or other characteristics of the traffic scenario, and therefore naturally and easily scales up to the full range of situations and scenarios encountered in real traffic. Measures that comprise individual rules or computations for specific traffic scenarios are inherently not scalable.
Table 2: Characteristics of Selected Traffic Collision Hazard Measures

| Characteristic         | SHM | TTC | RSS | ISM | Disengagements | IMU |
|------------------------|-----|-----|-----|-----|----------------|-----|
| 1. Leading             | ✓   | ✓   | ✓   | ✓   | ✓              |     |
| 2. Quantitative        | ✓   | ✓   | binary | binary | binary      | ✓   |
| 3. Continuous          | ✓   | ✓   | count\(^a\) | count\(^a\) | count\(^a\) | count\(^a\) |
| 4. Independent         | ✓   | ✓   | ✓   | ✓   | ✓              |     |
| 5. Direct              | ✓   | ✓   | ✓   |     |                |     |
| 6. Repeatable          | ✓   | ✓   | ✓   | ✓   |                | ✓   |
| 7. No Assumptions      | ✓   | ✓   | ✓   |     |                |     |
| 8. Monotonic           | ✓   |     |     |     |                |     |
| 9. Objective           | ✓   | ✓   | ✓   |     |                |     |
| 10. Computable         | ✓   | ✓   | partial\(^b\) | ✓       | ✓              |     |
| 11. Scalable           | ✓   | ✓   | ✓   |     |                |     |

\(^a\) Occurrences of events are counted, and therefore are not a continuous measure.
\(^b\) Two of the RSS rules are computable; the remainder are not.

2.2 Streetscope Collision Hazard Measure (SHM)

The novel measure of vehicle and traffic risk and safety described here utilizes the position and velocity of the subject vehicle, the position and velocity of each traffic object, the road conditions, and an estimate of the maneuverability of the subject vehicle and traffic objects (maximum safe braking deceleration rate and maximum safe turning rate). Table 2 presents a comparison of the characteristics of selected traffic collision hazard measures.

In all cases, the measure is computed sequentially for the subject vehicle in relation to each traffic object. For a subject vehicle and eight traffic objects, the measure will be computed in a pair-wise manner: eight times at each time step, once for each traffic object in relation to the subject vehicle.

The essence the measure incorporates the square of the the relative speed between the subject vehicle and a traffic object \(S_{rel}\) divided by the distance that separates the vehicle and the object \(d_{sep}\).

\[
m_2 = \frac{S_{rel}^2}{d_{sep}} \tag{9}
\]

\(m_2\) has the units of \([\text{length}/\text{time}^2]\) or \([\text{acceleration}]\).

This measure has the essential character of near-misses described above, combining proximity (separation distance) and motion (relative speed) for each pair of traffic objects in a traffic scenario (e.g., car-pedestrian) at each frame of sensor data. In this case, relative speed is in the numerator, so the measure will be larger for larger values of relative speed; separation distance is in the denominator so that the measure will be larger for smaller separation distances.

This matches our perception of near-misses. A vehicle that is moving at 0.5 m/s (1 mph) past a pedestrian at a distance of 1 meter (39 inches) would not be alarming or considered to be particularly dangerous. In contrast a vehicle that is moving at 30 m/s (67 mph) past a pedestrian at the same distance would be highly alarming and would be considered to be seriously dangerous. Both relative speed and separation distance are essential characteristics of a quantitative measure of near-misses, and the hazard that they produce.
The influence of the speed of the subject vehicle in relation to the traffic object is considerably magnified in $m_2$ compared to other approaches to quantify near-misses. This magnification is desired, and is an important characteristic of the measure since the square of the speed is directly proportional to the kinetic energy of the subject vehicle in relation to the traffic object and the dissipation of kinetic energy in a collision is the cause of damage and injury.

An augmented version of the measure incorporates the square of the maximum of the absolute speed of the subject vehicle ($S_{abs}$) and the relative speed between the subject vehicle and a traffic object ($S_{rel}$) divided by the distance that separates the vehicle and the object ($d_{sep}$).

$$m_3 = \max(S_{abs}, S_{rel})^2 / d_{sep}$$

$m_3$ also has the units of $[\text{length}/\text{time}^2]$ or $[\text{acceleration}]$.

This approach to combining a compensated (i.e., squared) value of relative speed with separation distance has the essential characteristic of monotonicity: a less severe traffic hazard will result in a lower numerical value of the measure than a more severe traffic hazard.

Importantly, the determination of the measure values makes no assumptions nor predictions about the behavior or actions of traffic objects; it simply assesses the current state of the near-miss interaction between each pair of objects, and does not predict future actions, decisions or trajectories.

Because the measure can be computed from simple low-cost sensors that are independent of the automated on-board sensing and decision-making, the SHM treats the vehicle, and those around it in traffic, as a “black-box”, and the results are a fully independent measure of the hazards encountered by a vehicle in traffic, and its responses to those hazards.

### 2.3 Further Augmented Streetscope Collision Hazard Measure

Additional features of the SHM have been implemented, including incorporation of road/street surface characteristics (traction or grip\(^3\)) and estimates of the limits of maneuverability of each traffic object (e.g., minimum turning radius, braking distance, perception-reaction time). These further augmentations will be presented in future publications.

Both U.S. and International patents are pending. [1, 2]

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\(^3\)Road/street traction or grip can be estimated from video imagery, or can be measured independently periodically, or can be determined from an on-board traction-control system. Estimates of grip will be presented in future publications.
3 Example Illustrations

3.1 Simulation

Simulations were used as the starting point to demonstrate how the SHM works, and to illustrate its effectiveness and utility.

Figure 4 shows three frames from a simulation of traffic, overlaid with various displays of the results of the computation of the SHM. The display shows an overhead view of a 4-way intersection with various vehicles and other traffic objects.

In the simulation, the subject vehicle (or ego vehicle) is a car, shown as a bright blue rectangle, traveling in the Eastward direction. The ego vehicle has a red border in these three frames, illustrating that it is encountering hazard values that are in the Unsafe range.

There are three other cars in the scenario: a green car heading South, a light-purple car heading West, and a light blue car traveling East somewhat ahead of the ego vehicle.

In addition to the cars, there is a bus, shown as the bright purple elongated rectangle, heading Northward across the intersection. There are also 3 bicycles, shown as green cigar-shapes; two pedestrians heading North across the intersection shown as small circles, and two fire hydrants, shown as small squares.

Since this simulation is an ego-centric scenario, where our interest is solely in the hazard encountered by the ego vehicle, and not on the interactions between the other traffic objects, a line is drawn on the simulation between the ego vehicle and the center of each of the traffic objects. These lines illustrate the results of the computation of the SHM by the width and color of the line.4

- A thin white line indicates that there is no hazard being encountered between the ego vehicle and the traffic object. This situation occurs, for example, if the ego vehicle and the traffic object are moving away from each other.

- A slightly thicker green line indicates that there is a hazard value that has been computed between the ego vehicle and the traffic object, but the value is in the Safe range.

- A thicker yellow line indicates that the collision hazard value between the ego vehicle and the traffic object is in the Hazardous range.

- A thick red line indicates that the collision hazard value between the ego vehicle and the traffic object is in the Unsafe range.

The speed of the ego vehicle is displayed in its rectangle, along with the largest collision hazard value encountered among the visible traffic objects at this time. Each traffic object also has its speed and individual collision hazard value (if visible to the ego vehicle) displayed.

No collisions occur in this simulation, however, there are a number of very close near-misses, by design, to exercise and demonstrate the SHM.

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4Note that two thresholds have been established for values of the SHM: a transition from Safe to Hazardous, and a transition from Hazardous to Unsafe. These thresholds, in practice, will be set by regulatory authorities to help identify the safety/riskiness of driving behaviors. For the purposes of the simulation shown here, the thresholds have been set arbitrarily, as an illustration.
Figure 4: Three frames from a simulation of the collision hazard measure.
A graph of all hazard values is being created in the bottom left corner of each frame of the simulation. The vertical axis is the value of the SHM, and the horizontal axis corresponds to the position of the center of the ego vehicle. Each line, colored to match the color of the traffic object that generated the collision hazard value, is displayed. As can easily be seen, these values rise and fall as the separation distance grows smaller and larger (respectively) and/or the relative speed grows larger and smaller (respectively).

A histogram of the SHM values encountered up to this frame is being created in the top left corner of the simulation frame, along with various other representations and aggregations of the SHM values.

### 3.2 On-street Data

Over 2 years of data has been collected and analyzed from vehicles operating on streets in traffic. One frame from a visualization of analyzed data is included in Figure 5, as an example.

SHM performed well with the complexities of vehicles in real urban traffic, real sensors (with the attendant sensor noise, object visibility, detection and tracking anomalies, and consequent data processing challenges, *e.g.*, estimating position and speed of objects from monocular imagery).

Future publications will examine on-street data in greater detail.
Figure 5: An example frame of a visualization of on-street data with the collision hazard measure values.
4 Conclusions

Leading indicators for measuring and assessing the safe operation of vehicles in traffic are essential to the deployment of automated mobility. Existing approaches, such as TTC, RSS, ISM, IMU data, and disengagements, do not provide the information required to provide a measurement of safety that will be useful to regulators and the public. The existing methods all require assumptions and/or predictions about the behaviors of traffic objects, which will not, in general, be correct, limiting the value of the information that they provide.

Lagging indicators, such as historical collision statistics, do not provide timely information, and require the ethically unacceptable occurrence of collisions, property damage, injuries and deaths.

The Streetscope collision hazard measure (SHM) has the essential characteristics to provide a measurement of safety that will be useful to regulators and the public. It overcomes the limitations of existing measures, provides an independent leading indication of safety, and does not require assumptions nor predictions of behaviors. The measure will also be directly useful for vehicle developers, to independently monitor and assess engineering progress; to fleet operators to monitor and improve ongoing operational safety; to traffic managers to identify areas that generate high hazards and to guide remediation and design efforts; and to insurers to facilitate effective analysis of risk.

Many areas of application of the SHM include route selection (whether for human-driven or automated vehicles), to balance the competing objectives of speed, fuel efficiency, and safety. Routes that include areas (such as intersections) that have a history of many high-value near-misses would be penalized, and therefore avoided, in the balanced selection.
A Measurement Scales

A.1 Properties

Each scale of measurement satisfies one or more of the following properties of measurement. [25]

- **Identity.** Each value on the measurement scale has a unique meaning.
- **Magnitude.** Values on the measurement scale have an ordered relationship to one another. That is, some values are larger and some are smaller.
- **Equal intervals.** Scale units along the scale are equal to one another. This means, for example, that the difference between 1 and 2 would be equal to the difference between 19 and 20.
- **Zero.** A minimum value of zero. The scale has a true zero point, below which no values exist.

A.2 Selected Scale Types

**Ordinal Scale of Measurement:** The ordinal scale has the property of both identity and magnitude. Each value on the ordinal scale has a unique meaning, and it has an ordered (and therefore monotonic) relationship to every other value on the scale. [25]

**Ratio Scale of Measurement:** The ratio scale of measurement satisfies all four of the properties of measurement: identity, magnitude, equal intervals, and a minimum value of zero. [25]

A.3 Ratio Scales

Ratio scales are those most commonly encountered in physics and are possible only when there exist operations for determining all four relations: equality [identity], rank-order [magnitude], equality of intervals, and equality of ratios [zero]. . . All types of statistical measures are applicable to ratio scales . . . [23]

[The ratio scale] level of data measurement allows the researcher to compare both the differences and the relative magnitude of numbers. Some examples of ratio scales include length, weight, time, etc. [26]
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