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Design of a Rear-end Collision Prevention System (RCPS)

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Abstract: Rear-end collisions occur when there is an insufficient stopping distance between vehicles when the braking action by the following driver commences. Rear-end collisions make up one-third of all vehicle accidents annually. These accidents pose a risk to life and incur damage costs anywhere between $500 to over $5000 while disproportionately affecting those with lower financial resources. Determining safe following distances relies on drier education and guidelines, however, and analysis conducted showed that 81% of vehicles were not complying with these standards nor values that were calculated through physics-based simulations. A system that provides cues to drivers on the road to what appropriate following distances should have the ability to eliminate the estimation that are demanded of drivers and has the potential to increase the number of drivers that are maintaining a safe following distance.

Keywords: Rear-end Collision, Following distance, Stopping distance, Sudden stop, Vehicle separation

1. Introduction and Context Analysis

A bow-tie analysis based on a model of rear-end collisions, identified that rear-end collisions can be prevented by the following car maintaining a safe separation distance from the lead car, such that when the lead car stops suddenly, there is enough time for the following car to stop without a collision. Determining a safe following distance is a fundamental aspect of safe driving, often guided by the "2-, 3-, and 4-second rule" recommended by the Department of Motor Vehicles (DMV). The manual also suggested increasing the following distance under certain conditions such as bad weather conditions, traffic, or poor road conditions (*Virginia Driver's Manual,* 2023). However, the practical application of this rule can be complicated by the cognitive demands of driving itself.

1.1 Statistics of Rear-end Collisions

There are over 2,000,000 rear-end collisions each year, all of which have immense financial and emotional consequences. There are over 500,000 injuries and 2,000 fatalities from this type of accident alone (Bubalo, 2021). Additionally, rear-end collisions can cause property damage that ranges from $500 to over $5,000 (*How much does the average,* 2024). According to the Federal Highway Administration (FHWA), the number of licensed drivers in the United States is increasing each year, with a projected number of drivers at almost 260 million in 2025 (*Number of licensed drivers in the US,* 2024). Additionally, the U.S. Department of Energy reports that the number of vehicle miles traveled in the United States has grown significantly and it is estimated that the number of miles traveled per year in 2025 will be over 3.5 trillion (*Maps and data,* 2023).

1.2 Factors Causing an Increase in REC

1.2.1 Weather

Weather conditions exert a significant influence on the occurrence of rear-end collisions due to several key factors. Elements like rain, snow, and ice dramatically reduce road traction, leading to a loss of vehicle control, thereby increasing the likelihood of collisions. Moreover, reduced visibility during inclement weather further compounds the risk, impairing a driver's ability to perceive and react to sudden stops or obstacles on the road. Findings in 2023 highlight the increased difficulty drivers face in avoiding collisions when weather conditions hamper braking effectiveness (*Can weather or road defects cause a rear-*

end accident, 2023). The escalating impact of climate change exacerbates these challenges by intensifying the frequency and severity of extreme weather events (Leard & Roth, 2016).

1.2.2 Human Factors

Human factors stand as a dominant contributor to the escalating incidence of rear-end collisions on roads, driven by various elements of driver behavior and inattentiveness. Distracted driving and driver inattention, fueled by factors like smartphone usage, pose a substantial threat to road safety. The sobering statistics reveal a harrowing reality, with approximately 3,000 fatalities annually attributed to distracted driving, claiming nine lives every day (*Distracted driving,* n.d). Moreover, the concerning trend of increased phone usage while driving has only exacerbated, with drivers spending an average of 1 minute and 38 seconds on their phones per hour of driving. (*Distracted driving,* n.d).

2. Stakeholder Analysis

2.1 Objectives

Stakeholders have been divided into three tiers. Tier 1 is the stakeholders that are directly involved with the system, Tier 2 is the stakeholders that are responsible for incident response, and Tier 3 is the stakeholders that are associated with the design of the environment. Interviews with an auto accessories entrepreneur, transportation systems engineer, insurance agent, and a traffic operation engineer as well as drivers have been conducted to obtain valuable information relevant to this problem. Below are the stakeholders, tiers they belong to, and primary objectives:

2.2 Stakeholder Transaction Diagram

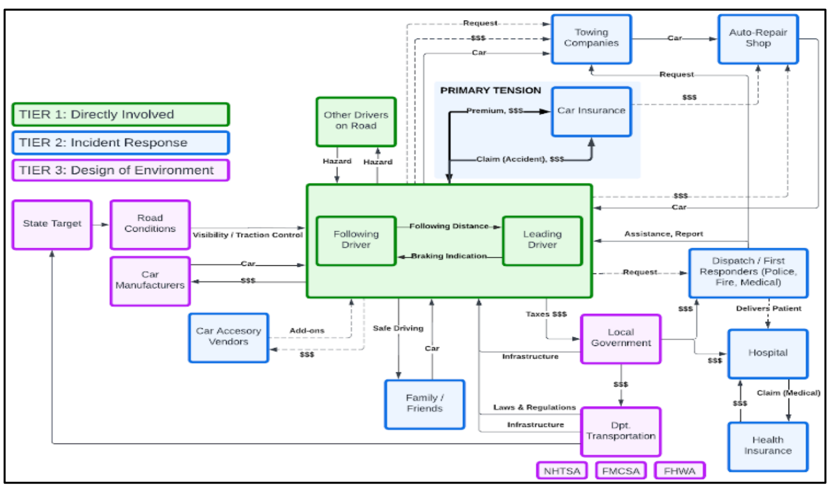

Figure 1. Stakeholder Transaction Diagram

2.3 Tensions

The government has imposed safety regulations and standards in the automotive industry for decades. The high interest and influence of USDOT, VDOT, and NHTSA. FMCSA and FHWA ensure the safety of drivers on the road. However, road regulations between VDOT and other state DOTs may pose conflicts as there are differing standards with additional lighting and aftermarket accessory add-ons. Other tensions that may arise between the stakeholders include decreased insurance rates and property damage thus identifying it as the primary tension for this system. Car insurance increases by 45% on average after one at-fault car accident (Metz, 2023). In some states such as North Carolina, even not-at fault drivers can expect their car insurance premium to increase by about 4% (*How much does car insurance go,* 2022). The system aimed at collision prevention may lower rates, causing less profit for the insurance companies due to fewer claims and lower premiums. This tension has been identified as the primary tension for this system, as highlighted in Figure 1.

3. As-Is Process

3.1 Pre-Collision

The As-Is process is the most generic-bare bones model. Within this model exists three entities. The following and lead drivers as well as VDOT. In a typical scenario, the drivers involved are driving and based on their knowledge of VDOT's safe following distance standards, they estimate their following distance from the lead vehicle. Performance gaps identified within this As-Is process are the needs for drivers to accurately estimate distances from the lead car and adjust accordingly based on speed, weather and a myriad of other factors.

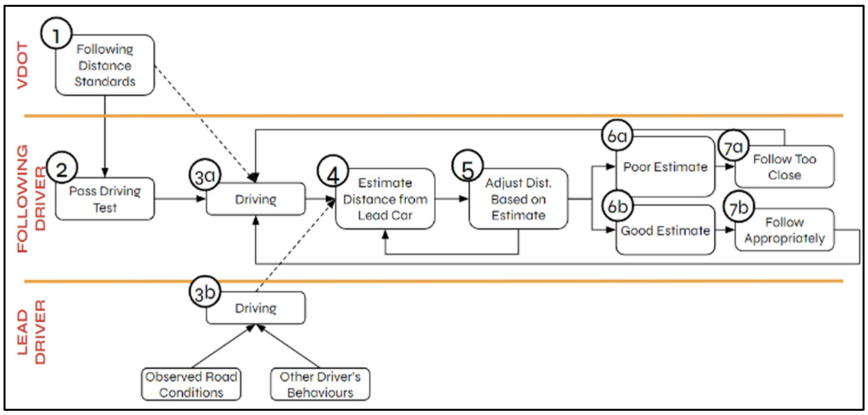

Figure 2. As-Is Process: Pre-Collision

4. Physics of REC

Using Simulink's Vehicle Dynamics Block set, a simulation was done to compare the effect of velocity, road slickness and required stopping distance. The results demonstrated that velocity contributed to a more significant change in the required stopping distance. A non-linear relationship between velocity and required stopping distance. This is to be expected; the faster one goes, the more distance they would need to come to a stop. However, the nonlinearity of the relationship presents itself as an issue as it is well understood that humans struggle to conceptualize non-linear relationships.

5. Performance Gap

The functional gap was identified as a lack of following distance between vehicles. Following vehicles do not have the necessary time to come to a stop if the lead vehicle were to slam on their brakes. From the As-Is process, it was identified that there is no cue that indicates to drivers what that gap should be; drivers are forced to make their own estimations. The conclusion was made that drivers do not have the appropriate tools or know-how to correctly estimate appropriate following distances.

6. Problem and Need Statement

In investigating rear-end collisions, it is apparent that safe following distances are not being maintained by most drivers, reason being that (1) drivers do not know the correct safe following distance given the current circumstances and (2) drivers do not know how to maintain the correct safe following distance. So as a result, when braking occurs, following drivers cannot slow/stop in time. According to safety calculations, a minimum safe following distance must be maintained for a standard vehicle to brake in time without causing a rear-end collision; this distance varies based on contributing factor inputs. A video analysis on Braddock Road has demonstrated that 81% of drivers fail to maintain a safe following distance. A solution is necessary that will decrease that percentage. That specific case study will be discussed in section 10.1.

The need for a reliable and accurate rear-end collision prevention device arises from the frequency of rear-end collisions on roadways, resulting in significant damages. Current vehicle safety systems fall short in providing sufficient protection against rear-end collisions, necessitating an advanced and proactive solution that can be retrofitted to older vehicles without modern safety features, as well as forward fitted to vehicles that have some modern safety features.

7. Concept of Operations and To-Be Process

7.1 Concept of Operations

The rear-end collision prevention system is designed to reduce fatalities, injuries, and property damage caused by rear-end collisions. The cause of these collisions is a lack of following distance. When the following car is too close to a leading car, when the leading car hits their brakes, the following car does not have enough time to slow down, resulting in the collision. By taking into consideration the relative velocities of vehicles involved, traffic flow dynamics, driver braking habits, road conditions, and visibility, a system has been created that helps vehicles to identify safe following distances. This signals to the driver that they must increase their following distance to remain in a safe range.

7.2 To-Be Process

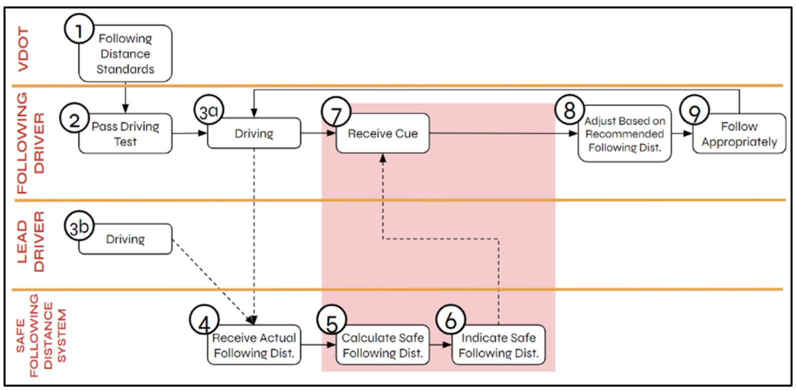

Figure 3. To-Be Process

In the As-Is process, it has been revealed that drivers are only estimating their following distance to the driver in front of them, having only the knowledge of following distance standards provided by the VDOT. There is a lack of cue to indicate to the driver whether they are in fact maintaining a correct safe following distance. This is where the fourth entity in the To-Be process comes in. The system in the diagram can receive the actual following distance between the lead and the following driver, calculate the safe following distance, and indicate the safe following distance to the following driver. The blocks in the shaded area as shown in Figure 3, are where the prominent changes from the As-Is process are indicated.

8. Requirements

8.1 Example of Mission Requirements

- **MR.1** The system shall indicate to the following vehicle the appropriate following distance by calculating the lead and following vehicle velocities, avoiding a collision if the lead vehicle suddenly slows or stops.

8.2 Example of Design Requirements

- **DR.1.3** The system lighting brightness shall be Department of Transportation (DOT) and Society of Automotive Engineers (SAE) approved.a collision.

8.3 Example of Functional Requirements

- **F.1** The system shall measure the distance from the lead vehicle to the following vehicle using radar technology and the time for the electromagnetic wave to reflect back, using the formula $s = c/t$.

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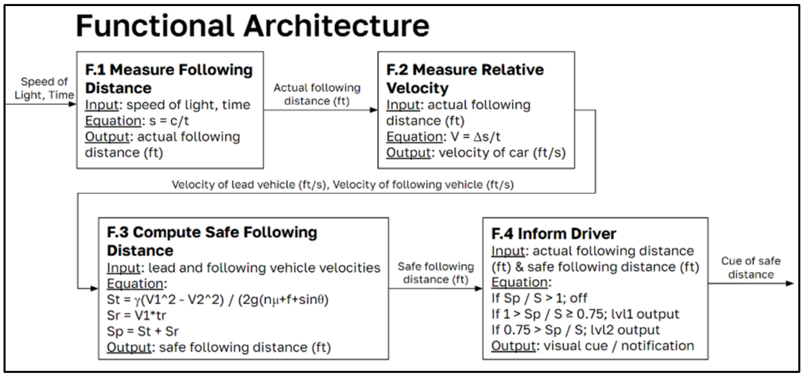

Figure 4. Functional Architecture

9. Design

9.1 Design Alternatives

With the performance gap identified as the lack of following distance between vehicles due to the lack of visual cues to indicate the insufficient following distance, various design alternatives were considered: a rear-facing following distance indicator, a dashboard-mounted device, use of a safe driving application on a mobile phone and a bumper sticker that encourage safe driving.

9.2 Utility Analysis

A Multi-Attribute Utility Theory (MAUT) analysis was conducted, where each engineering requirement for the system was treated as an alternative, which was then ranked from most important to least important, where most important was most necessary to comply with. The top two requirements were the system's ability to comply with any applicable road laws and the system's ability to indicate the following distance. From there, weights were assigned to each of the requirements and an assessment method was determined as shown in. A single dimensional linear value function was formed for each requirement using the assessment parameters. Next, each design alternative received scores for each requirement, which were inputted into the value functions and used to determine performance in each requirement. Scores were scaled according to the ranking of requirements and used to output a final utility for each design alternative. The design alternative with the greatest utility was the rear-facing following distance indicator. A Utility vs Cost to Consumer plot is constructed to analyze the design alternatives and a mock design of a license plate frame with distance sensor using accelerometer to measure vehicle velocity and display LEDs was developed as shown in Figure 5. The LEDs provide a visual cue to the following car to indicate a safe or unsafe following distance.

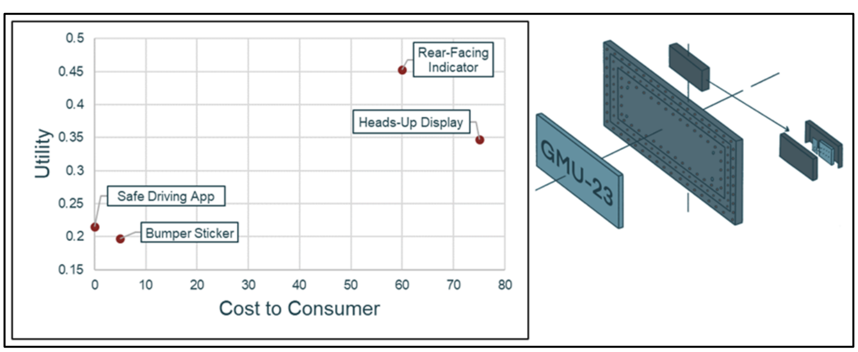

Figure 5. Analysis of Design Alternatives and Rear-facing Following Distance Indicator (Mock-up Design)

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10. Con-Ops Validation Study

10.1 Braddock Road X Roanoke River Road

Data was collected on the cross between Braddock Road and Roanoke River Road. This area was chosen for data collection due to the large volume of traffic that is commonly pushed through the area. The speed limit being 40mph allowed data to be collected at relatively higher speeds. In total, 164 cars were recorded, weather conditions were dry and sunny. For the sake of this analysis, the following assumptions were made: vehicle speed followed N(40,3), all vehicles were operating at the legal minimum brake efficiency of 0.435, the coefficient of friction was 1 (dry and sunny), as well as driver reaction time was set to 1.5s as recommended by research. It was seen that the average time between cars was 2.156s with a standard deviation of 0.899s. A one-tailed Z test was then conducted and was found that the p-value was significantly smaller than α. Thus, the null hypothesis was rejected, and it was found that there was statistical evidence to support the claim that the average was not maintaining a minimum practical gap between themselves and the lead vehicle. It is important to question why no rear-end collisions were witnessed. This is mainly because there was no hard braking and weather conditions were ideal: there was no catalytic event that would be required to have a rear-end collision.

11. Conclusion

Rear-end collisions pose a significant threat on U.S. roads, resulting in injuries, fatalities, and property damage. The key issue lies in the failure to maintain safe following distances between vehicles, exacerbated by weather conditions, road infrastructure, technological challenges, and human behaviors like distraction. Stakeholder analysis revealed diverse interests, emphasizing the need for collaboration among auto manufacturers, insurance companies, government agencies, and transportation engineers. In conclusion, the complex nature of rear-end collisions requires a holistic approach involving technological innovation, human behavior understanding, stakeholder collaboration, and continual refinement of the proposed simulation model. Implementing an effective RCPS holds promise in significantly reducing rear-end collisions and promoting safer roads.

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