8-2013

Development of Stationary and Mobile Tailgating Detection Solutions for Ground Vehicles

Tyler Zellmer
Clemson University

Follow this and additional works at: https://tigerprints.clemson.edu/all_theses
Part of the Mechanical Engineering Commons

Recommended Citation
Zellmer, Tyler, "Development of Stationary and Mobile Tailgating Detection Solutions for Ground Vehicles" (2013). All Theses. 2303.
https://tigerprints.clemson.edu/all_theses/2303

This Thesis is brought to you for free and open access by the Theses at TigerPrints. It has been accepted for inclusion in All Theses by an authorized administrator of TigerPrints. For more information, please contact kokeefe@clemson.edu.
DEVELOPMENT OF STATIONARY AND MOBILE TAILGATING DETECTION SOLUTIONS FOR GROUND VEHICLES

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Mechanical engineering

by
Tyler Zellmer
August 2013

Accepted by:
Dr. John R. Wagner, Committee Chair
Dr. Kim Alexander
Dr. Mohammed Daqaq
ABSTRACT

Improving the safety of North American roadways is a top priority for government agencies and transportation organizations alike. Regulations on appropriate driving behavior have been developed to minimize the likelihood of crashes occurring, but law enforcement tools remain to be fully developed and applied in the field. One prominent example of this is tailgating – the dangerous act of one ground vehicle following another too closely. This activity is responsible for thousands of crashes every year, but police officers currently have few tools to accurately detect and document tailgating events. Though tailgating often occurs in a wide variety of vehicle scenarios, the most hazardous class of tailgating is that which occurs when a semitrailer, more commonly called an 18-wheeler, follows a passenger vehicle too closely. The difference in mass between a semitrailer and a passenger vehicle results in a stopping distance nearly twice as long for the former. In addition, truck drivers may be fatigued and unable to react as quickly to emergency situations, further increasing the risk of a deadly crash. Therefore, a tool is necessary that enables officers to determine when tailgating occurs, and allows them to document the event for use by prosecutors in a court of law.

Two mechatronic tools, one stationary and one mobile, have been proposed to detect and document tailgating events. The proposed stationary system continuously observes and reports tailgating in a given lane of traffic through the use of commercially available hardware and a novel tailgating detection algorithm. This algorithm determines a safe following distance time gap using velocity information provided by the onboard range finding sensors and basic vehicle dynamics equations. Nearby officers are
immediately notified that a violation has occurred, and data concerning the event is recorded for future retrieval. The system has the ability to distinguish between tractor trailers and passenger vehicles to specifically isolate occurrences of truck tailgating. A numerical simulation of the stationary tailgating detection system is developed and presented, and the virtual system accurately detects vehicle presence and velocity for speeds of up to 50 m/s (112 mph). The effects of resolution and vehicle velocity on the accuracy of the system were investigated. Additionally, a scale hardware prototype was developed to further examine the validity of the proposed algorithm.

The mobile tailgating detection system employs a scanning laser range finder in conjunction with data processing algorithms to determine the location of surrounding vehicles. Once identified, an appropriate minimum separation distance between two target vehicles is determined using information provided by the scanner and host vehicle, in addition to standard vehicle dynamics equations. An estimation of the target vehicles’ separation distance is determined with 95% confidence through one-second samples and standard statistical analysis. Subsequently, a compounding distance-dependent penalty is assessed against violators of the minimum following distance. If a vehicle’s penalty count exceeds a defined threshold, then a tailgating situation has occurred. A numerical simulation was developed and presented to test the validity of the algorithm. Many multi-vehicle cases are examined in which all tailgating events were successfully detected.

Future work in the detection and recording of ground vehicle tailgating should include the development of full-scale prototypes and extensive field trials, undertaken in conjunction with law enforcement, to reduce roadway tailgating events.
ACKNOWLEDGMENTS

I want to sincerely thank everyone involved in the process of my education over the last 5 years as a student of Clemson University.

First I would like to thank Dr. John Wagner for the guidance and support he has provided both while I was an undergraduate student and as a graduate student. This project really pushed the limits of my abilities to be independent and self-sufficient, in addition to broadening my technical horizons. I would also like to extend thanks to Dr. Kim Alexander and Dr. Philip Pidgeon of the Clemson University Institute for Global Road Safety and Security for their assistance in the completion of this project, in addition to Dr. Mohammad Daqaq for participating as a committee member.

In addition, I want to thank my parents, Russ and Angela Zellmer, whose support has pushed me and encouraged me to reach beyond what I thought was possible. Their support and encouragement have shaped me into the person I’m now proud to be. Finally, I want to thank God for blessing me with the opportunity to learn, grow and achieve as I have.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITLE PAGE</td>
<td>i</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>ix</td>
</tr>
<tr>
<td>NOMENCLATURE LIST</td>
<td>xii</td>
</tr>
<tr>
<td><strong>CHAPTERS</strong></td>
<td></td>
</tr>
<tr>
<td>I. INTRODUCTION TO TAILGATING</td>
<td>1</td>
</tr>
<tr>
<td>Tailgating: A Big Problem</td>
<td>5</td>
</tr>
<tr>
<td>Scale Prototype</td>
<td>7</td>
</tr>
<tr>
<td>Organization</td>
<td>10</td>
</tr>
<tr>
<td>II. AN AUTONOMOUS STATIONARY TAILGATING SYSTEM</td>
<td>12</td>
</tr>
<tr>
<td>Introduction</td>
<td>12</td>
</tr>
<tr>
<td>Technology Overview of Detection System</td>
<td>14</td>
</tr>
<tr>
<td>Case Study</td>
<td>24</td>
</tr>
<tr>
<td>Summary</td>
<td>28</td>
</tr>
<tr>
<td>III. A MOBILE TAILGATING DETECTION SYSTEM</td>
<td>29</td>
</tr>
<tr>
<td>Introduction</td>
<td>30</td>
</tr>
<tr>
<td>Tailgating Technology and Physics</td>
<td>32</td>
</tr>
<tr>
<td>Overview of Tailgating System</td>
<td>43</td>
</tr>
<tr>
<td>Case Study</td>
<td>45</td>
</tr>
<tr>
<td>Summary</td>
<td>57</td>
</tr>
</tbody>
</table>
Table of Contents (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV. CONCLUDING REMARKS AND FURTHER RESEARCH</td>
<td>58</td>
</tr>
<tr>
<td>Summary of Discussion</td>
<td>58</td>
</tr>
<tr>
<td>Future Work</td>
<td>59</td>
</tr>
<tr>
<td>APPENDICES</td>
<td>63</td>
</tr>
<tr>
<td>A: Arduino Code for Hardware Prototype</td>
<td>64</td>
</tr>
<tr>
<td>B: Stationary Tailgating Detection Numerical Simulation</td>
<td>76</td>
</tr>
<tr>
<td>C: Mobile Tailgating Detection Numerical Simulation</td>
<td>82</td>
</tr>
<tr>
<td>D: Penalty Assessment MATLAB Code</td>
<td>93</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>94</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 Crashes involving large trucks by severity and point of impact</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Prototype system test results for scale vehicle traveling at varying speeds</td>
<td>10</td>
</tr>
<tr>
<td>2.1 Model parameters to calculate theoretical stopping distances</td>
<td>21</td>
</tr>
<tr>
<td>2.2 Initial conditions for tailgating system simulation</td>
<td>25</td>
</tr>
<tr>
<td>3.1 Constants used in estimation of minimum following distance which correspond to typical real-world vehicle values</td>
<td>35</td>
</tr>
<tr>
<td>3.2 System tuning parameter values used in simulation</td>
<td>46</td>
</tr>
<tr>
<td>3.3 Initial conditions for vehicle tailgating simulation, in which no tailgating occurs</td>
<td>47</td>
</tr>
<tr>
<td>3.4 Initial conditions for second simulated scenario, in which tailgating occurs for a limited time</td>
<td>49</td>
</tr>
<tr>
<td>3.5 Initial conditions for second simulated scenario, in which tailgating occurs</td>
<td>51</td>
</tr>
<tr>
<td>3.6 Initial conditions for simulated three-vehicle scenario, no tailgating occurs</td>
<td>53</td>
</tr>
<tr>
<td>3.7 Initial conditions for three-vehicle simulated scenario, in which Vehicle 1 follows too closely and Vehicle 2 tailgates</td>
<td>55</td>
</tr>
</tbody>
</table>


LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Areas through which the problem of tailgating may be addressed</td>
<td>3</td>
</tr>
<tr>
<td>1.2</td>
<td>Photograph of a tractor trailer tailgating a vehicle, taken on Interstate 85 North near Greenville, SC</td>
<td>4</td>
</tr>
<tr>
<td>1.3</td>
<td>Illustration of safe following distance d behind a vehicle traveling at speed</td>
<td>7</td>
</tr>
<tr>
<td>1.4</td>
<td>Photograph of prototype system</td>
<td>8</td>
</tr>
<tr>
<td>2.1</td>
<td>Side view of proposed stationary tailgating system</td>
<td>16</td>
</tr>
<tr>
<td>2.2</td>
<td>Signal flow through proposed tailgating detection system</td>
<td>17</td>
</tr>
<tr>
<td>2.3</td>
<td>Free body diagram of two-axle vehicle deceleration model</td>
<td>19</td>
</tr>
<tr>
<td>2.4</td>
<td>Minimum following distance for a loaded tractor trailer following a passenger vehicle</td>
<td>24</td>
</tr>
<tr>
<td>2.5</td>
<td>Decay of accuracy as simulated 5m long vehicle speed increases</td>
<td>26</td>
</tr>
<tr>
<td>2.6</td>
<td>Flow chart of prototype system operation</td>
<td>27</td>
</tr>
<tr>
<td>3.1</td>
<td>Operational diagram of scanning laser range-finder</td>
<td>33</td>
</tr>
<tr>
<td>3.2</td>
<td>Plot of the minimum safe distance by which a tractor trailer must follow a passenger vehicle, as calculated by $d_{\text{min}}$, using standard values listed in Table 3.1</td>
<td>35</td>
</tr>
<tr>
<td>3.3</td>
<td>Illustration of output from rotating laser range finder for angle, where points A-D are defined previously</td>
<td>37</td>
</tr>
<tr>
<td>3.4</td>
<td>Illustration of vehicle detection scenario</td>
<td>38</td>
</tr>
<tr>
<td>3.5</td>
<td>Diagram of vehicle locations showing calculated values</td>
<td>41</td>
</tr>
</tbody>
</table>
List of Figures (Continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6</td>
<td>Flow chart for prototype system mobile tailgating monitoring algorithm</td>
</tr>
<tr>
<td>3.7</td>
<td>Penalty function for two-vehicle scenario in which no tailgating occurs</td>
</tr>
<tr>
<td>3.8</td>
<td>Numerical response of the laser range reading vs. scan angle for a semitrailer following a passenger vehicle at velocity and initial separation distance listed in Table 3.3</td>
</tr>
<tr>
<td>3.9</td>
<td>Penalty function for two-vehicle scenario in which Vehicle 1 tailgates the lead vehicle for approximately 1 second</td>
</tr>
<tr>
<td>3.10</td>
<td>Numerical response of the laser range reading vs. scan angle for a semitrailer following a passenger vehicle at velocity and initial separation distance listed in Table 3.4</td>
</tr>
<tr>
<td>3.11</td>
<td>Penalty function for two-vehicle scenario in which Vehicle 1 tailgates the lead vehicle for approximately 1 second</td>
</tr>
<tr>
<td>3.12</td>
<td>Numerical response of the laser range reading vs. scan angle for a semitrailer following a passenger vehicle at velocity and initial separation distance listed in Table 3.5</td>
</tr>
<tr>
<td>3.13</td>
<td>Penalty function for three-vehicle scenario in which no tailgating occurs</td>
</tr>
<tr>
<td>3.14</td>
<td>Numerical response of the laser range reading vs. scan angle for a semitrailer following two passenger vehicles at velocity and initial separation distance listed in Table 3.6</td>
</tr>
<tr>
<td>3.15</td>
<td>Penalty function for two-vehicle scenario in which Vehicle 1 tailgates the lead vehicle for approximately 1 second</td>
</tr>
<tr>
<td>3.16</td>
<td>Numerical response of the laser range reading vs. scan angle for a semitrailer following two passenger vehicles at velocity and initial separation distance listed in Table 3.7</td>
</tr>
<tr>
<td>A.1</td>
<td>Pseudocode flow chart for Arduino prototype system</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>A.2</td>
<td>A connection diagram for the prototype system using an Arduino micro controller</td>
</tr>
<tr>
<td>A.3</td>
<td>A wiring schematic for the prototype stationary detection system</td>
</tr>
<tr>
<td>B.1</td>
<td>Logic flow through simulation of stationary tailgating detection system</td>
</tr>
<tr>
<td>C.1</td>
<td>Logic flow through proposed mobile tailgating solution</td>
</tr>
</tbody>
</table>
NOMENCLATURE LIST

\( a_d \) Vehicle deceleration (G)

\( c \) Speed of light (m/s)

\( C_d \) Vehicle drag coefficient

\( d \) Distance between vehicles required for safe stop (m)

\( d \) Sample mean distance (m)

\( d_i \) Sample distance measurement (m)

\( d_i \) Distance between laser sensors (m)

\( d_{\text{min}} \) Minimum following distance (m)

\( d_{\text{min}}^* \) Estimated minimum following distance (m)

\( d_s \) Distance to laser target (m)

\( F_b \) Total braking force (N)

\( F_{bf} \) Applied brake force for the front axle (N)

\( F_{br} \) Applied brake force for the rear axle (N)

\( f_r \) Tire rolling resistance coefficient

\( g \) Gravity (m/s\(^2\))

\( H \) Hypothesis

\( l \) Vehicle length (m)

\( N \) Number of samples gathered in one second

\( n_{\text{min}} \) Minimum number of data points for accurate reading

\( p \) Vehicle penalty count

\( p_{\text{max}} \) Penalty count limit
Nomenclature List (Continued)

q  Internal vehicle ID number
r  Laser range reading (m)
rs  System resolution (m)
rt  Driver reaction time estimation (s)
ΣR  Resistance forces (rolling, aero, weight) (N)
Ra  Applied aero resistance force (N)
Rr  Applied rolling resistance force (N)
S  Vehicle frontal area (m²)
s  Vehicle position (m)
t  Safe following gap time (s)
tcalc  T-score test statistic
ts  Laser beam time of flight (s)
v  Vehicle velocity (m/s)
W  Vehicle weight (N)
x  Lateral vehicle location (m)
y  Longitudinal vehicle location (m)
α  Confidence interval
β  Best fit coefficients
Δs  Stopping distance (m)
Δt  Time step (s)
Δθ  Change in laser range finder angle (deg)
Nomenclature List (Continued)

\( \gamma_b \) Driveline inertia coefficient

\( \eta_b \) Braking efficiency

\( \Gamma \) Tailgating distance-based penalty calibration parameter

\( \kappa \) Tailgating event penalty function

\( \kappa_{dec} \) Amount that vehicle penalty is reduced for each step

\( \theta \) Angle of laser range finder (deg)

\( \theta_s \) Angle of roadway with respect to ground (deg)

\( \mu \) Roadway friction coefficient

\( \rho \) Air density (kg/m\(^3\))

\( \sigma \) Sample standard deviation

\( \theta \) Angle of laser range finder (deg)

\( \theta_c \) Angle of camera (deg)

\( \omega_{rr} \) Laser refresh rate (Hz)

\( \omega_p \) Laser pedestal rotational velocity (rad/s)
CHAPTER ONE
INTRODUCTION TO TAILGATING

Approximately 1.24 million people are killed every year in traffic related incidents [1]. In the United States alone, there were an estimated 32,885 traffic deaths in 2013. Traffic crashes are the leading cause of death amongst teenagers in the United States, accounting for 35% of annual teenage deaths between 1999 and 2006 [2]. Clearly, crashes are a significant health risk that must be addressed. Given the immense array of causes, it makes sense to select a particular area to address. In 2010, large trucks were involved in approximately 206,000 crashes with other vehicles, according to the NHTSA [3]. Of these crashes, 31.3% were ones in which a large truck rear-ended a passenger vehicle, as seen in Table 1.1. More importantly, the front of the vehicle is listed as the point of impact for nearly 60% of crashes resulting in fatalities. These crashes may be largely attributed to the common practice of following a vehicle too closely, known as tailgating.

<table>
<thead>
<tr>
<th>Initial Point of Impact</th>
<th>Crash Severity</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fatal Percent</td>
<td>Injury Percent</td>
</tr>
<tr>
<td>Front</td>
<td>59.3</td>
<td>43.9</td>
</tr>
<tr>
<td>Left Side</td>
<td>11.2</td>
<td>18.7</td>
</tr>
<tr>
<td>Right Side</td>
<td>6.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Rear</td>
<td>20.6</td>
<td>19.7</td>
</tr>
<tr>
<td>Noncollision</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Other/unknown</td>
<td>2.8</td>
<td>2.1</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>
There are three main areas through which the issue of tailgating may be addressed, shown in Figure 1.1. These areas are driver training, enforcement, and vehicle and roadway factors such as speed limits and in-vehicle notification. As tailgating is an act that may be easily avoided, enough emphasis is clearly not made in driver training programs. If truck driving programs emphasized the importance of maintaining a safe following distance more earnestly, the occurrence of tailgating-related crashes might be reduced. Further, the development of in-vehicle warning systems to notify the driver of unsafe following conditions could help eliminate the ability of driver’s to claim ignorance. However, the main problem lies in the fact that – for the majority of motorists – tailgating is an action without consequence. Currently, no tools exist to enforce safe following behavior amongst motorists. With truck drivers in particular, who are often paid by the mile, the incentive is to arrive at one’s destination as fast as possible, even if this includes encouraging passenger vehicles to move out of the way by tailgating. For this reason, the primary focus of this thesis is the development of tools to aid law enforcement in the detection and documentation of truck tailgating.
Figure 1.1: Areas through which the problem of tailgating may be addressed

Generally speaking, tailgating is a more significant problem on interstates and highways, where trucks can travel at high speeds. For example, it is the experience of the author that trucks on Interstate 85 between Atlanta, GA and Charlotte, NC often travel at 10 to 15 kph (6 to 9 mph) over the posted speed limits. The photograph in Figure 1.2 was taken by the author on this specific stretch of road. At times, this is faster than traffic in even the leftmost lane, which results in truck drivers following passenger cars very
closely. Truck drivers seem to do this to encourage slower drivers to change lanes. In addition to being dangerous in its own right, this act often has the effect of making the lead driver nervous or angry. Subsequent unpredictable behavior may then occur, such as brake checking, wherein the lead driver suddenly applies the brakes to scare the following driver. This may begin a chain reaction, resulting in at least a disruption in traffic flow, and at worst a fatal traffic crash. If a safe following distance is maintained, the risks of road rage and rear-end crashes are greatly reduced.

Figure 1.2: Photograph of a tractor trailer tailgating a vehicle, taken on Interstate 85 North near Greenville, SC (Credit: Tyler Zellmer)
I. Tailgating: A Big Problem

The main reason that tractor-trailer tailgating in particular is such a problem is that tractor-trailers take much longer to stop from speed than passenger vehicles. An average loaded tractor trailer requires 166m to stop from a speed of 113 kph [4]. By comparison, a 2013 Hyundai Accent takes only 53m to stop from the same speed [5]. Furthermore, the risk of death to a passenger in a light car involved in an incident with a heavy truck is 44 times higher than in an incident between two light cars [6]. Clearly, truck-car crashes are very dangerous, and following too closely is very likely to result in a crash should an emergency braking situation arise for the lead vehicle.

A secondary concern with tailgating is that the following driver’s reaction time may not be quick enough should an emergency situation arise. Following too closely narrows the window during which a driver must react, placing significant importance on the abilities of the following driver. Truck drivers are often tasked with covering long distances in a given day, and may be driving for up to 8 hours at a time. In fact, a 2007 study found that 13% of commercial motor vehicle crashes could be attributed to driver fatigue [7]. The practice of tailgating seems to have become an unconscious driving habit [6], as opposed to an action carried out for particular benefit. Many drivers simply do not realize – or care - that, should an emergency arise, they will not be able to react in time. As the relative velocity of the lead vehicle in comparison to the driver’s vehicle is often zero, and emergency braking situations appear somewhat rarely, most drivers are comfortable with tailgating. The fact that a lifetime of tailgating may not result in a crash falsely reinforces the idea that the activity is safe, and so it continues.
The statistics discussed have demonstrated thoroughly that tailgating is not safe. Many states have legislation requiring that vehicles follow at a distance that is reasonable and prudent [8]. Unfortunately, law enforcement officers have no tools at its disposal to detect when tailgating occurs, or to prove that it happened when in court. This document outlines two possible solutions to this problem. Proposed are two systems that can detect and report tailgating to law enforcement officials. Both systems use basic vehicle dynamics equations to determine a safe following distance, illustrated in Figure 1.3. First, a system is proposed that is to be placed above a given lane of traffic, where it observes vehicles traveling below. When tailgating occurs, the event is recorded and a nearby officer is notified. A second system is proposed that, when installed on an officer’s vehicle, scans the environment around the vehicle for tailgating violators. When a tailgating event is detected, the environmental conditions such as location and speed are recorded and the officer is notified. A novel feature in both systems is the use of vehicle dynamics equations to determine an appropriate following distance for the given traffic conditions. Together, these systems harbor the potential to reduce tailgating on America’s roadways, resulting in fewer traffic injuries and deaths. In addition to tailgating detection and documentation capabilities, the proposed systems have the secondary ability to monitor road use data, including vehicle speed, traffic conditions, and other metrics.
II. SCALE PROTOTYPE

A prototype system was developed in order to demonstrate the stationary prototype algorithm. The system consisted primarily of a Rugged Circuits Ruggeduino microcontroller, a solderless breadboard, and two HC-SR04 ultrasonic range finding sensors. Ultrasonic technology was used in lieu of laser technology due to cost considerations – though the range of the prototype system is lessened by this change, the fundamentals of operation remain the same. The assembled system also includes a number of LED’s to display feedback to the operator. The system was assembled on an inexpensive breadboard to reduce iteration time, with the two ultrasonic range sensors placed next to each other along the direction of vehicle travel. Simple 18 gauge, single strand, shielded wire was used to connect the various electrical components. Power was
supplied by the laptop to the Arduino. A photograph of the prototype system is provided in Figure 1.4.

![Figure 1.4: Photograph of prototype system, including (1) Arduino microcontroller, (2) notification LED’s and (3) ultrasonic range finders](image)

The system operates continuously in the following manner. Upon initialization, the system obtains a baseline measurement to the pavement. Then, the leading distance sensor measures the distance from the sensor to the pavement at a rate of 20Hz. If a measurement is returned that is different from the baseline by more than a specified amount (indicating the presence of a vehicle), the system immediately begins measuring using the trailing distance sensor. At this time, the system initiates a timer. Once the vehicle passes under the trailing sensor, the timer is stopped and – knowing the distance between sensors – the vehicle’s velocity is calculated. An appropriate following distance is then calculated based on the vehicle’s velocity, and the system switches back to using
the leading sensor for vehicle detection. A count-down timer is then begun, during which any vehicle that passes under the system is guilty of tailgating. Code for the prototype system was written in the Arduino’s native language, which is itself an extension of the C programming language. The ultrasonic-based system was successfully able to measure a target vehicle’s velocity, calculate an appropriate following time, and detect the presence of a tailgating vehicle. The Arduino code is listed in Appendix A, in addition to system diagrams and schematics.

A test was devised to validate the prototype system. Of interest is the ability of the system to detect both the presence and velocity of an object in its range. The system was placed approximately 18 inches from a wall. Since the system zeroes itself upon initial power up, no calibration is required. The “roadway” consisted of a series of equidistant lines on the ground, above which a camera was placed. Since the frame rate of the camera was known, it was possible to calculate the velocity of the vehicle during each test by dividing the distance traveled between two frames by the time between each frame, using the road’s grid for reference. The pointed nose of the vehicle was used to place the vehicle in each frame as accurately as possible, using the nearest visible line as reference. The results of 10 trials at varying speeds are shown in Table 1.2.

The mean difference between the camera and system reported speed was 2.97 cm/s with a standard deviation of 18.59 cm/s. There are two primary causes for this uncertainty. Firstly, the blurriness of the photo made interpreting its position a difficult task. This was caused by the relatively low frame rate and shutter speed of the video camera used. Secondly, the prototype system uses ultrasonic range-finding sensors to
measure distance instead of laser sensors. While much less expensive, these sensors are less accurate and more easily fooled by moving objects. However, the mean difference was very low, supplying evidence for the validity of this concept. A numerical simulation of this system, operating at higher speeds, is discussed in Chapter 2.

<table>
<thead>
<tr>
<th>Run</th>
<th>Vehicle (cm/s)</th>
<th>Camera (cm/s)</th>
<th>Difference (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>76.20</td>
<td>65.69</td>
<td>-10.51</td>
</tr>
<tr>
<td>2</td>
<td>80.96</td>
<td>65.69</td>
<td>-15.27</td>
</tr>
<tr>
<td>3</td>
<td>57.15</td>
<td>66.26</td>
<td>9.11</td>
</tr>
<tr>
<td>4</td>
<td>152.40</td>
<td>119.06</td>
<td>-33.34</td>
</tr>
<tr>
<td>5</td>
<td>95.25</td>
<td>119.06</td>
<td>23.81</td>
</tr>
<tr>
<td>6</td>
<td>19.05</td>
<td>34.79</td>
<td>15.74</td>
</tr>
<tr>
<td>7</td>
<td>38.10</td>
<td>65.69</td>
<td>27.59</td>
</tr>
<tr>
<td>8</td>
<td>114.30</td>
<td>120.95</td>
<td>6.65</td>
</tr>
<tr>
<td>9</td>
<td>66.68</td>
<td>66.26</td>
<td>-0.41</td>
</tr>
<tr>
<td>10</td>
<td>9.53</td>
<td>15.88</td>
<td>6.35</td>
</tr>
</tbody>
</table>

### III. Organization

The remainder of this thesis is organized in the following manner. Chapter Two outlines the stationary tailgating detection system, including a discussion of vehicle dynamics, micro processing and laser range estimation technologies, and a numerical simulation. Chapter Three discusses the proposed mobile tailgating detection solution, with appropriate laser range finding techniques and behavior penalty assessment. A numerical simulation is also discussed. Chapter Four concludes the discussion of these
systems and offers future research opportunities. The code used in the scale prototype of the stationary system is offered in Appendix A. The MATLAB code developed for the numerical simulation of the stationary system is shown in Appendix B. Appendix C contains the MATLAB code written for the numerical simulation of the mobile system. The penalty function used in the numerical simulation of the mobile system is provided in Appendix D.
CHAPTER TWO

AN AUTONOMOUS STATIONARY TAILGATING DETECTION SYSTEM

In this chapter, a new system is proposed that can remotely and autonomously detect and report the occurrence of tailgating. The system continually adjusts to varying required following distances given flux in traffic speed. It can also discern the difference between large trucks and passenger vehicles, and can provide law enforcement with photographic evidence of violation. The system consists of two laser range-finding sensors placed over the roadway, a computer processor, battery pack and a camera. A functional prototype was developed to demonstrate proof of concept. A camera and grid system was used to validate the ability of the system to detect vehicles and measure their speed, and the system accurately detected a low-speed scale vehicle. A virtual model of the system simulates higher speeds, and the system was found to be accurate at up to 50 m/s (180kph). This validates the proof of concept, and shows that the Autonomous Stationary Tailgating Detection System has the potential to encourage safe driving habits amongst truck drivers, while providing law enforcement with a tool to enforce existing laws.

I. INTRODUCTION

According to the NHTSA, motor collisions account for nearly 2.4 million injuries and 37 thousand fatalities each year [3]. In the same study, it was revealed that over 40% of these crashes occurred through a truck rear-ending a light duty vehicle. It is for these reasons that the South Carolina Driver’s Manual suggest that “a truck should not follow
another truck or any motor vehicle pulling another motor vehicle closer than 300 feet.” [9] Unfortunately, truck drivers often ignore this suggestion, and tailgate as a means of saving fuel, or communicating to the driver in front of them that they wish to pass. Many states have passed laws preventing this – for example, South Carolina outlawed following closer than is “reasonable and prudent” [8], but these laws are difficult to enforce. A logical first step in preventing these types of incidents would be to provide law enforcement with the tools to document definitive cases of tailgating, in the hopes of encouraging safer driving.

Current automotive range finding techniques focus primarily on locating vehicles for the purposes of adaptive cruise control. Laser-based systems have been devised using advanced mirror shapes to locate vehicles on a roadway that is not level [10]. Many systems place a vehicle into a grid once it is detected [11] so that the processor can more easily determine what control input is necessary. These inputs and algorithms allow adaptive cruise control systems to form an understanding of the vehicle’s surroundings. An extension of this technology can be viewed in current research efforts to develop an entirely autonomous vehicle. These prototype vehicles typically use a combination of laser, radar and optical sensors [12] to develop a virtual representation of the environment. However, very little research has been performed in this area with regards to vehicle tailgating. The system proposed in this chapter uses these environmental-awareness techniques in to determine the distance between two vehicles.

The proposed system is a portable, autonomous system that can detect and report cases of tailgating on any highway with an accessible overpass. It consists of an
integrated microcontroller, two laser rangefinders, a camera, a radio, and a battery or generator. A mathematical relationship will be derived to estimate the stopping distance of both a loaded tractor-trailer and a standard passenger vehicle. A speed-dependent “safe following distance” formula is developed based on both stopping distance estimates and used to detect when tailgating occurs. The system is built on open-source hardware and software to allow future development, as well as to keep component costs to a reasonable minimum. A small-scale prototype of the system was constructed to demonstrate the soundness of the tailgating detection method. The remainder of this chapter is as follows: the technology and theories employed in the proposed device are outlined in Section II. Section III details the numerical simulation developed to demonstrate these theories. Section IV concludes the discussion.

II. TECHNOLOGY OVERVIEW OF DETECTION SYSTEM

Two main technologies are used to develop the proposed motor vehicle monitoring system: first, laser-based distance estimation techniques are discussed, followed by an overview of the widely-available, open-source Arduino microcontroller platform. A mathematical foundation for the estimation of safe following distance based on empirical data is developed.

A. Laser-based Distance Estimation

Laser range-finding techniques are used to detect the existence and classification of a vehicle passing under the monitoring system. A number of common laser range-finding techniques exist; the method implemented in this project operates by measuring
the time it takes for a short burst of light to reflect off the object in question. This method employs a laser, optical sensor, and very high-accuracy timing hardware to calculate the absolute distance from the sensor to the object. Specifically, the system operates by firing a number of narrow-beam, high-frequency laser pulses towards an object. In basic terms, distance can be estimated as

\[ d_s = \frac{c \cdot t_s}{2} \]  \hspace{1cm} (2.1)

The following discussion pertains to the LightWare DS00 laser rangefinder used in the proposed system [13]. First, laser light is generated by firing a laser diode for 30ns. The optical sensor must then detect a return signal of sufficient strength within a certain time limit to make an estimation of distance. Signal strength is ensured by setting a threshold of magnitude, in addition to pulse width. Pulses that do not meet the requirements for either magnitude or pulse width are treated as noise and not counted. To further eliminate noise, both the leading and trailing edges of the detection pulse must occur within the specified time limit.

Since the time required for light to bounce off the target surface may in fact be less than the time it takes for the processor to send and receive signals, a “zero signal” is sent through the entire system as well. The difference in time between the zero signal and the return signal is then measured to get the time of flight, and from this the distance to the target.

B. System Hardware Using Open-Source Microcontroller

The proposed system is designed to be installed on an existing over-road structure, such as an overpass or road sign. Once installed, the system will continuously
monitor one lane of traffic for the occurrence of tailgating. It will report tailgating events to area law enforcement personal, in addition to storing evidence of the event on-board, for retrieval and later use in court. A top-level diagram of the system is shown in Figure 2.1. The system is comprised of a CCD camera, two laser-based rangefinders, a battery power supply, a microcontroller, an SD card storage device, a radio, and an LCD display.

![Figure 2.1: Side view of proposed stationary tailgating system layout - (1) tractor trailer, (2) passenger vehicle, (3) laser rangefinders, and (4) processing equipment](image)

Signal flow through the system is outlined in Figure 2.2. The Arduino-based microcontroller receives signal input from the laser rangefinder at 20Hz. If a tailgating event is detected, each configurable output is activated to perform its designated function. First, details about the event including speed, time, and calculated following distance are recorded to an SD card for storage and later retrieval. News of the event is also transmitted instantly via radio communication to all nearby officers, in addition to being displayed on the integrated LCD screen. Finally, a picture is taken using the CCD camera, and stored on the SD card for later use as evidence in court. The entire system
receives power from a 12-volt battery power source, such as a commercial car battery or UPS.

![Diagram of tailgating detection system]

Figure 2.2: Signal flow through proposed tailgating detection system; SD is Secure Digital, CCD is Charge Coupled Device

The system detects tailgating as follows. Once placed over the roadway in question, the system obtains a baseline distance to the road below using one of the two laser rangefinders. When a vehicle passes below the machine, it is detected through a change in the distance registered by the laser rangefinder. The time it takes for the vehicle to pass from one sensor to the next is used to calculate the vehicle’s velocity, where

$$v = \frac{s_1 - s_2}{\Delta t}$$  \hspace{1cm} (2.2)

Once the vehicle’s velocity has been determined, Equation (13) can be employed to calculate an appropriate time gap. Once the leading vehicle has completely passed under the system, a timer begins counting up to the minimum time gap. If a truck passes under the system before the time gap has expired, a tailgating event has occurred. The difference between a passenger vehicle and a truck can be determined by the difference in height, as measured by the laser rangefinder.

The Arduino platform has made a significant impact in the electronics sphere due to its low cost and open platform. The platform is based on the ATmega microcontroller.
architecture. The most popular Arduino model, the Uno, features an ATmega328 microcontroller running at 16MHz, 2kb of RAM, 14 digital I/O pins, 6 analog I/O pins and PWM output on 6 pins [14].

The platform features a standardized form factor, which allows the development of add-on boards to increase functionality. These add-on boards, called shields, allow the Arduino platform to control and communicate with almost any device. For example, shields exist that enable radio communication, camera operation, and even LCD screens. There currently exists a laser range-finding add-on board for the Arduino platform that is accurate to 1cm at up to 100m [13]. It features industrial-grade optics and built-in timing circuitry. The Arduino platform provides a free, open-source software package to develop and upload routines to the Arduino hardware. The programs are written in C, and a wide array of libraries are available that provide additional functionality.

In the event that further processing power is required, the openness of the Arduino platform has enabled the development of boards based on much more advanced processors. One manufacturer has developed a board that follows the standard Arduino form factor but sports a 72MHz SMT32 microcontroller and 128kb RAM. This greatly increases the processing power available to the user, while keeping price low and without losing compatibility with existing Arduino software and hardware [15].

C. Estimation of Vehicle Stopping Distance

To estimate an appropriate following distance, it is first necessary to estimate the required stopping distances of the vehicles in question. The method below is widely used,
and derived from the Newtonian dynamics of a simple 2-axle vehicle model [16]. A free-body diagram of this vehicle model, showing only relevant forces, is shown in Figure 2.3.

Figure 2.3: Free body diagram of two-axle vehicle deceleration model

The forces active in the longitudinal direction may be developed using the free body diagram shown above as

\[ F_b + \sum R = \gamma_b \left( \frac{W}{g} \right) a_d = -\dot{v} \]  \hspace{1cm} (2.3)

where \( F_b = F_{bf} + F_{br} \) and \( \sum R = R_a + R_r \). The vehicle’s acceleration is then integrated to calculate vehicle displacement as a function of initial and final velocities. The basic relationship between acceleration and velocity as a function of distance is expressed \( \dot{v} = v \frac{dv}{ds} = -a_d \). This can be rewritten as \( -ds = v \frac{dv}{a_d} \), and then integrated: \( \int_{s_1}^{s_2} -ds = \int_{v_1}^{v_2} v \frac{dv}{a_d} \). Solving the first integral, an expression for distance travelled over a change in velocity can be written as \( -(s_2 - s_1) = -\Delta s = \int_{v_1}^{v_2} v \frac{dv}{a_d} \). By transferring the negative sign, this can be rewritten as \( \Delta s = \int_{v_2}^{v_1} v \frac{dv}{a_d} \). The stopping distance, \( \Delta s \), is the metric of interest, \( v_2 = 0 \), so that
\[ \Delta s = \int_{0}^{v_1} \frac{v \, dv}{a_d} \]  \hspace{1cm} (2.4) 

Equation (2.3) can be rewritten in terms of acceleration as 

\[ a_d = \frac{F_b + \Sigma R}{\gamma b g} \]  \hspace{1cm} (2.5) 

By substituting Equation (2.5) into Equation (2.4), a new formula for the following distance can be expressed as 

\[ \Delta s = \gamma b \left( \frac{\gamma b}{g} \right) \int_{0}^{v_1} \frac{v \, dv}{F_b + \Sigma R} \]  \hspace{1cm} (2.6) 

The sum of the deceleration forces can be rewritten per the free body diagram in Figure 2.3 as 

\[ F_b + \Sigma R = F_{bf} + F_{br} + W \sin \theta_s + R_r + R_a \]  \hspace{1cm} (2.7) 

where \( R_a = \frac{1}{2} \rho C_d S v^2 \) and \( R_r = f_r W \cos \theta_s \). Assuming that \( F_b, f_r \) and \( \theta_s \) are constant for the entire braking event, Equation (2.6) and Equation (2.7) can be combined and rewritten as 

\[ F_b + \Sigma R = F_b + f_r W \cos \theta_s + W \sin \theta_s + \frac{1}{2} \rho C_d S v^2 \] 

Let \( c_1 = F_b + f_r W \cos \theta_s + W \sin \theta_s \) and \( k = \frac{1}{2} \rho C_d S \) so that Equation (2.6) may be written as 

\[ \Delta s = \gamma b \left( \frac{\gamma b}{g} \right) \int_{0}^{v_1} \frac{v \, dv}{c_1 + kv^2} \]  \hspace{1cm} (2.8) 

Similarly, let \( u = c_1 + kv^2 \) and \( du = 2kv \, dv \). By substitution into Equation (2.8) and integration, it is possible to produce a general expression for the stopping distance, given as 

\[ \int_{0}^{1} \frac{v \, dv}{u} = \int_{c_1}^{u_1} \frac{du}{2ku} = \frac{1}{2k} \ln u \bigg|_{c_1}^{u_1} = \frac{1}{2k} \ln \frac{u_1}{c_1} \]  \hspace{1cm} (2.9a)
\[
\Delta s = \frac{\gamma_b W}{g} \frac{1}{2k} \ln \left( 1 + \frac{k v_1^2}{\frac{F_b + f_r W \cos \theta_s + W \sin \theta_s}{W(\mu + f_r)}} \right)
\] (2.9b)

For a vehicle with ABS, the assumption is made that all four wheels are in a “near lockup” state – that is, the braking force is defined as

\[F_b = \mu W\] (2.10)

Then, the braking efficiency may be defined to quantify the proportion of available traction that is used for deceleration as

\[\eta_b = \frac{\frac{a_d}{g}}{\frac{1}{\max}}\] (2.11)

For braking efficiency \(\eta = 1\) (i.e., all tires are being used for maximum deceleration), and on flat ground \((\theta_s = 0)\), Equations (2.10) and (2.11) can be combined with Equation (2.9) to produce a stopping distance estimation, given as

\[
\Delta s = \frac{W}{z g k} \ln \left( 1 + \frac{k v_1^2}{W(\mu + f_r)} \right)
\] (2.12)

When estimating the stopping distance \(\Delta s\), values for frontal area \(S\), air density \(\rho\), drag coefficient \(C_d\), weight \(W\) and other parameters are shown in Table 2.1. Typical values were used for weight, drag and frontal area [17].

**Table 2.1: Model parameters to calculate theoretical stopping distances**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_{d,\text{car}})</td>
<td>0.35</td>
<td>-</td>
<td>(W_{\text{truck}})</td>
<td>356,000</td>
<td>N</td>
</tr>
<tr>
<td>(C_{d,\text{truck}+\text{trailer}})</td>
<td>0.76</td>
<td>-</td>
<td>(\beta_1)</td>
<td>4.90 (10^3)</td>
<td></td>
</tr>
<tr>
<td>(f_r)</td>
<td>0.01</td>
<td></td>
<td>(\beta_2)</td>
<td>2.18 (10^{-5})</td>
<td></td>
</tr>
<tr>
<td>(g)</td>
<td>9.81</td>
<td>m/s(^2)</td>
<td>(\beta_3)</td>
<td>2.36 (10^3)</td>
<td></td>
</tr>
<tr>
<td>(r_t)</td>
<td>1.5</td>
<td>s</td>
<td>(\beta_4)</td>
<td>3.14 (10^{-5})</td>
<td></td>
</tr>
<tr>
<td>(S_{\text{car}})</td>
<td>1.91</td>
<td>m(^2)</td>
<td>(\gamma_b)</td>
<td>1.05</td>
<td>-</td>
</tr>
<tr>
<td>(S_{\text{truck}})</td>
<td>9.386</td>
<td>m(^2)</td>
<td>(\mu)</td>
<td>0.75</td>
<td>-</td>
</tr>
<tr>
<td>(W_{\text{car}})</td>
<td>18,000</td>
<td>N</td>
<td>(\rho)</td>
<td>1.16</td>
<td>kg/m(^3)</td>
</tr>
</tbody>
</table>
Using the equations and parameters discussed above, the stopping distance from 129kph (80mph) was calculated to be approximately 91.25m (299.4ft) for a 18,000N (~4,000lbs) car and 92.17m (302.4ft) for a 356,000N (~80,000lbs) truck. While this estimation is fairly accurate for a small vehicle, it is not for the large truck. The assumption of 100% braking efficiency – that all available traction is being utilized for deceleration – is a close approximation for modern passenger vehicles with advanced ABS systems, but does not apply to a loaded tractor-trailer, which may or may not have ABS at all. In addition, the ideal brake force distribution – i.e. one that keeps all four wheels on the verge of locking – varies with road friction [17], further reducing braking efficiency. For a braking efficiency of less than one, Equation (2.12) can be written as

$$\Delta s = \frac{W}{2gk} \ln \left(1 + \frac{k v_1^2}{W(\eta b \mu + f_r)}\right)$$  \hspace{1cm} (2.13)

In addition, a two axle model is less accurate for a multi-axle semi-trailer. However, through extensive experimentation [14] a braking efficiency may be determined that allows a two-axle model to closely approximate the actual stopping distance of a many-axle vehicle. For stopping calculations regarding a passenger vehicle, a braking efficiency of $\eta_c = 0.90$ was used; for the loaded truck, $\eta_t = 0.62$ [18]. Using these values and Equation (2.13), stopping distance was calculated from 0 kph to 193 kph (120 mph). With the revised braking efficiency parameters, a stop from 129 kph (80 mph) is now projected to take approximately 40m (310 feet) for a passenger vehicle and 137m (450 feet) for a loaded truck.
D. Minimum Safe Following-Distance Estimation

An equation for the minimum “time gap,” i.e. the minimum safe time between vehicles, has been developed using the calculated stopping distance values. For both vehicles to come to a stop at the same time, the following distance at a given velocity must be given by \( d(v) = \Delta s_1(v) - \Delta s_2(v) \), with the assumption that both vehicles are traveling at the same velocity. Combining the data provided in Table 2. with Equation (13) yields Equation (14), which describes a velocity-dependent required minimum following distance in meters. This mathematical function is shown in Figure 2.4.

\[
d(v) = \beta_1 \ln(1 + \beta_2 v^2) - \beta_3 \ln(1 + \beta_4 v^2)
\]

(2.14)

where parameters \( \beta_1 - \beta_4 \) are listed in Table 2.. With the basic understanding that \( t = \frac{d}{v} \), an expression for an appropriate “time gap” can be written. An additional amount of time must be taken into account in order to allow for driver reaction and for braking force to develop in the truck [19].

\[
t(v) = r_t + \frac{d(v)}{v}
\]

(2.15)
III. CASE STUDY

To validate the theories presented in the previous section, a numerical simulation was devised and run a number of times. First, a 3-dimensional (x,y,t) virtual representation of a highway environment was created. Virtual vehicle sensors were placed at known locations at a given length apart. Then, the environment was populated with vehicles of given length, lane location, initial location and velocity. The simulation was then executed. For each time step, the vehicle sensors monitored the environment for

![Graph showing minimum following distance for a loaded tractor trailer following a passenger vehicle.](image)

Figure 2.4: Minimum following distance for a loaded tractor trailer following a passenger vehicle
the presence of a vehicle. As previously discussed, the leading sensor began a velocity timer once a vehicle was located. This timer was stopped once the vehicle reached the second timer, from which the vehicle velocity was calculated. Using this velocity, an appropriate following distance was determined using the assumptions and formulas discussed earlier, and the tailgating timer was begun. If another vehicle passed through the first sensor before this tailgating timer expired, then the vehicle was marked as a tailgater. This logic flow is shown in Figure 2.6. The initial conditions for the simulation are presented in Table 2.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_s$</td>
<td>0.01, 0.02</td>
<td>m</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>0.001</td>
<td>S</td>
</tr>
<tr>
<td>$d_l$</td>
<td>1</td>
<td>m</td>
</tr>
<tr>
<td>$l$</td>
<td>5</td>
<td>m</td>
</tr>
</tbody>
</table>

It was found that a vehicle’s presence and speed could be calculated to within 4% at up to 50m/s, or 112mph. A plot of the difference between the velocity detected by the system and the velocity specified in the initial conditions is shown in Figure 2.5. In addition, the effect of resolution $r_s$ on the accuracy of the reported velocity is demonstrated in Figure 2.5; the 0.01m resolution simulations were more accurate overall than those performed at 0.02m. In both cases, the deviation below 50m/s may be largely attributed to rounding errors in the simulation.
Figure 2.5: Decay of accuracy as simulated 5m long vehicle speed increases

In addition to the numerical simulation, a low-speed hardware test was performed using off-the-shelf components. Ultrasonic range-finding sensors were employed rather than laser hardware. The system was accurately able to detect and estimate the speed of a scale vehicle traveling at modest speed, providing further proof of this concept’s validity.
Figure 2.6: Flow chart of prototype system operation
IV. SUMMARY

In conclusion, a portable, easily deployed device was designed that can detect and report vehicle tailgating. The system can be deployed on any overpass with a shoulder, and can operate continuously for as long as a battery can supply power. An algorithm was devised to calculate appropriate following distance after detecting vehicle speed using empirical data, and a numerical simulation provided evidence that the system holds merit. A preliminary prototype system was devised that can be built using open-source, readily available technology. The proposed system requires no special training to operate, and can be deployed in minutes without interrupting traffic. This system gives law enforcement the ability to detect tailgating, and provide defensible evidence of such in court. Existing tailgating requirements can therefore be more rigorously enforced, giving truck drivers and motorists further reason to drive safely. A tool such as this has the potential to greatly reduce the number of tailgating-related crashes on public freeways.
CHAPTER THREE

A MOBILE TAILGATING DETECTION SYSTEM

Automotive crashes occur each year due to semitrailers following passenger vehicles too closely on interstate highways and secondary roads. Called tailgating, over 40% of the 110,000 trailer-passerger vehicle crashes recorded by the NHTSA in 2010 may be attributed to this hazardous practice. As this phenomenon is difficult to detect and document using visual methods, law enforcement depends on available trained officers, whose abilities may be limited. In this paper, a proposed tailgating detection system, mounted to the officer’s patrol vehicle, continuously monitors both passenger and commercial vehicles as the officer travels down the roadway. A rotating laser range-finding sensor feeds information to a microprocessor that continuously searches for the occurrence of tailgating. A weighting algorithm determines when a tailgating event has definitively occurred to reduce system sensitivity. If an event is detected, then the officer is notified with audio and visual cues, plus the timestamp is recorded with all relevant system information for later use in legal prosecution. In a virtual case study, the computer generated roadway environment was populated with vehicles of varying velocity and location. The detection algorithm successfully located all virtual vehicles and accurately determined tailgating events.
I. INTRODUCTION

Tractor-trailers can weigh up to 356,000N (80,000lbs) [20] and travel the roadways throughout North America. By comparison, an average passenger vehicle weighs around 18,000N (4,000lbs) [17] and travels the same roads. Therefore, a fully-loaded tractor trailer requires 166m (546ft) to come to a stop from 112kph (70mph) [4], whereas a 2013 Hyundai Accent takes only 53m (174ft) [5]. According to the 2010 N.H.T.S.A. Annual Report [3], over 40% of crashes involving tractor-trailers and passenger vehicles occurred between the front of a semi and the rear of a passenger vehicle. Many of these events are caused by tailgating, the practice by which one vehicle follows another at an unsafe distance. Ideally, all drivers will leave a distance ahead of them large enough that they can stop safely in an emergency situation. The legality of tailgating varies by state – some explicitly state a minimum following distance, while others specify that drivers should maintain a distance that is “reasonable and prudent” [8]. In reality, law enforcement has no practical way to enforce these rules – tailgating is very difficult to spot, and even more difficult to collect actionable evidence against for use in a court of law.

The ability to detect such events has until recently presented a monumental technical challenge. As such, a commercial solution has not yet been marketed, and little literature exists on the topic. However, recent advancements in automotive laser range-finding have given engineers the ability to continuously monitor a vehicle’s surroundings, including neighboring vehicles. These advancements were at first focused on automatic cruise control (ACC) applications, where forward facing radar was employed to detect
preceding vehicles [21]. These methods, along with basic vehicle classification algorithms [22], allowed the development of commercially available adaptive cruise control systems. A more advanced implementation of this technology is used in automated vehicle navigation prototypes. Researchers commonly use laser-based range finding sensors, in addition to other technologies, to create a digital representation of the environment around the vehicle [12]. Consequently, a need exists for a solution that leverages this information towards the goal of identifying dangerous driving behavior, such as tailgating.

This paper proposes a tailgating detection system that takes advantage of such advancements, and that will allow law enforcement to continuously collect information on tailgating events for use in ticketing and prosecution. The system consists of a laser range-finding sensor facing a mirror mounted on a rotating pedestal, which is itself mounted on the roof of the patrol vehicle. This continuously scanning laser creates a virtual picture of the surrounding environment by recording relative distance and angle measurements at defined intervals. These distance and angle data points are then analyzed for quality, and if the data is sufficient to detect distance between the two target vehicles, the distance measurement is made. A computer algorithm then calculates a minimum safe following distance using the velocity of the host vehicle, and if distance between the two target vehicles is below this minimum, tailgating is said to have occurred. The tailgating event is recorded in addition to other sensory information for use in legal prosecution, and the officer is notified that the event has occurred.
The remainder of this paper is as follows: the technology and theories employed in the proposed device are outlined in Section II. Section III details the combination of these theories to form the proposed system. A case study is contained in Section IV and the conclusion is offered in Section V.

II. TAILGATING TECHNOLOGY AND PHYSICS

Automotive technologies have been developed that allow the accurate measurement of a vehicle’s surroundings, and the prediction of a vehicle’s actions under emergency braking situations. Commercially available laser range-finding systems provide high resolution and refresh rate, information which can be used in combination with mathematical algorithms to determine a target vehicle’s following distance. In addition, an appropriate minimum following distance has been developed using fundamental vehicle dynamics equations.

A. Review Laser Range-Finding Methods

Typical range-finding systems operate by a method known as time-of-flight. These self-contained modules fire a sequence of high-frequency laser pulses at the target and measure the time it takes for this pulse to return to the sensor to calculate the intermediate distance. This method requires high-accuracy timing and control circuitry; advances in modern electronics have made this technology more accessible. One drawback of laser range-finding, in comparison to comparable radar or ultrasonic
solutions, is the very narrow field of view. To overcome this, laser range-finding sensors may be paired with rotating mirrors to form a larger “picture” of the surrounding environment, as shown in Figure 3.1. Coupled with equally advanced data recording systems, these sensors can provide a $\theta=360^\circ$ view of the environment at an angular resolution of up to $\Delta\theta=0.062^\circ$ and a usable range of over $r=250m$ [23]. Laser range finding devices such as these are often used on autonomous vehicles to form an accurate near-range estimation of a vehicle’s surrounding [22]. In this case, it is to detect the presence and location of multiple vehicles.

![Operational diagram of scanning laser range-finder](image)

**Figure 3.1**: Operational diagram of scanning laser range-finder: (1) laser range-finding assembly, and with (2) rotating mirror for rotational scanning

### B. Calculation of Appropriate Following Distance

To estimate an appropriate following distance for two vehicles, it is necessary to calculate the emergency stopping distance of both vehicles. The stopping distance $\Delta s$ of a vehicle may be approximated as
\[ \Delta s = \frac{w}{2gk} \ln \left(1 + \frac{kv_1^2}{W(n_b \mu + f_r)}\right) \quad (3.1) \]

where \( k = \frac{1}{2} \rho C_d S \) [20]. With standard values used for weight, drag coefficient, frontal area and other variables [17], the stopping distance of a fully loaded semitrailer from 129kph (80 mph) is approximately 137m (450 ft). For an average passenger vehicle, a stop from the same velocity takes only 40m (310 ft).

It is now possible to derive an expression for the minimum distance at a given speed. Holding all environmental variables constant, the difference in stopping distance between the two vehicles can be expressed as \( d_{\text{min}}(v) = \Delta s_1(v) - \Delta s_2(v) \), where \( s_1 \) is the stopping distance of a semitrailer and \( s_2 \) is the stopping distance of a passenger vehicle when both vehicles have the same initial velocity. For the purposes of the proposed system, it is appropriate to combine typical environmental variables and vehicle parameters into static values to more quickly approximate \( d_{\text{min}}(v) \), so that

\[ d_{\text{min}}^*(v) = \beta_1 \ln(1 + \beta_2 v^2) - \beta_3 \ln(1 + \beta_4 v^2) \quad (3.2) \]

where the parameters \( \beta_1 - \beta_4 \) are listed in Table 3.1. These parameters were determined by fitting a curve to \( d_{\text{min}} \) using standard vehicle dimensions as listed in Table 3.1. Figure 3.2 shows this calculated minimum stopping distance from 0 to 55m/s (123mph).
Table 3.1. Constants used in estimation of minimum following distance which correspond to typical real-world vehicle values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{d,car}$</td>
<td>0.35</td>
<td>-</td>
<td>$\beta_1$</td>
<td>$4.90 \times 10^3$</td>
<td>-</td>
</tr>
<tr>
<td>$C_{d,\text{truck+trailer}}$</td>
<td>0.76</td>
<td>-</td>
<td>$\beta_2$</td>
<td>$2.18 \times 10^{-5}$</td>
<td>-</td>
</tr>
<tr>
<td>$f_r$</td>
<td>0.01</td>
<td>-</td>
<td>$\beta_3$</td>
<td>$2.36 \times 10^2$</td>
<td>-</td>
</tr>
<tr>
<td>$g$</td>
<td>9.81</td>
<td>m/s$^2$</td>
<td>$\beta_4$</td>
<td>$3.14 \times 10^{-5}$</td>
<td>-</td>
</tr>
<tr>
<td>$S_{\text{car}}$</td>
<td>1.91</td>
<td>m$^2$</td>
<td>$\gamma_b$</td>
<td>1.05</td>
<td>-</td>
</tr>
<tr>
<td>$S_{\text{truck}}$</td>
<td>9.386</td>
<td>m$^2$</td>
<td>$\mu$</td>
<td>0.75</td>
<td>-</td>
</tr>
<tr>
<td>$W_{\text{car}}$</td>
<td>18,000</td>
<td>N</td>
<td>$\rho$</td>
<td>1.16</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$W_{\text{truck}}$</td>
<td>356,000</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.2: Plot of the minimum safe distance by which a tractor trailer must follow a passenger vehicle, as calculated by $d_{\text{min}}$, using standard values listed in Table 3.1
C. Vehicle Detection and Classification Method

A method of locating the relative positions of vehicles on the roadway must be developed to detect a tailgating event. The configuration shown in Figure 3.4 will be used in the following discussion. The vehicle located in the lower left (Vehicle 0) is called the “host vehicle”, and is the vehicle on which the tailgating detection system is installed. Two target vehicles (Vehicles 1 and 2) are depicted some distance ahead of the host vehicle and in a different lane. An approximation of the laser response as a function of angle is shown in Figure 3.3, where points A, A’, B, C and D are labeled. By locating these points, the distance between two vehicles can be determined, in addition to each vehicle’s length. For monitored vehicles located to the passenger side of the host vehicle, the five points of interest can be described as the following:

A:   Leftmost point on the trailing vehicle’s rear bumper (Vehicle 1)
A’:  Rightmost point on the trailing vehicle’s rear bumper (Vehicle 1)
B:   Leftmost point on the trailing vehicle’s front bumper (Vehicle 1)
C:   Leftmost point on the leading vehicle’s rear bumper (Vehicle 2)
D:   Leftmost point on the leading vehicle’s front bumper (Vehicle 2)

These points are determined by first calculating $\frac{dr}{d\theta}$, which is the rate of change of the laser’s range $r$ compared to its radial position $\theta$, defined discretely as

$$\frac{dr}{d\theta}\bigg|_{\theta_i} = \frac{r(\theta_i) - r(\theta_{i-1})}{\theta_i - \theta_{i-1}}$$  \hspace{1cm} (3.3)
Figure 3.3: Illustration of output from rotating laser range finder for angle $0 \leq \theta \leq \frac{\pi}{2}$, where points A-D are defined previously.
Figure 3.4: Illustration of vehicle detection scenario: (0) host vehicle, target (1) lead vehicle, (2) target follow vehicle

The primary points of interest are points B and C, as they are necessary to calculate the distance between the following vehicle (Vehicle 1) and the lead vehicle (Vehicle 2). Point B is marked by a discontinuous positive jump in r, which is the reading made by the laser. This indicates that the point of laser impact has left the front of the
following vehicle and arrived on the tailgate of the rear vehicle. Point C may be identified by a local minimum immediately following point B. Physically, point C is a minimum because it is the point on the leading vehicle at which the laser reading stops decreasing (as it traverses the bumper) and starts increasing (as it travels up the side of the vehicle). A local minimum may be determined analytically as the point where the derivative is zero. However, since the data recorded is discrete, it is better to look for a change in the sign of the variable $\frac{dr}{d\theta}$ than for a zero point, or for two concurrent data points where

$$SGN\left(\frac{dr}{d\theta}|_{\theta_{i-1}}\right) = -SGN\left(\frac{dr}{d\theta}|_{\theta_i}\right) \quad (3.4)$$

The distance $r$ to these points, and the angle at which they occurred $\theta$, are stored for use in the distance calculations.

Once locations B and C have been identified, the following distance, $d$, can be calculated by splitting $r_c$ and $r_b$ into their x and y components as

$$y_b = r_b \sin(\theta_b), \quad x_b = r_b \sin(\theta_b) \quad (3.5)$$

$$y_c = r_c \sin(\theta_c), \quad x_c = r_c \sin(\theta_c)$$

The distance $d$ between the two vehicles can then be calculated by subtracting $y_b$ from $y_c$ so that

$$d = y_c - y_b = r_c \sin(\theta_c) - r_b \sin(\theta_b) \quad (3.6)$$
Points A’, A and D can be located in the same way as points B and C. Point A’, the first being reached by the sensor, is marked by a discontinuous negative drop in r. Point A represents a local minimum, being the closest point on the following car to the host car. As with point B, point D will manifest itself as a discontinuous positive jump in r.

For this theoretical framework to apply, it is necessary that there be sufficient data points on each surface of the vehicle to determine a definite minimum or discontinuity. Assuming (A1) that the exposed surface of the leading vehicle’s rear bumper is the shortest as observed by the scanner, the frequency \( \omega_{rr} \) required to obtain n data points is

\[
\omega_{rr} = \frac{n \omega_p}{\theta_{cb}}
\]

(3.7)

where \( \omega_p \) is the rotating velocity of the scanner and \( \theta_{cp} = \theta_c - \theta_b \). A tailgating event is said to be observable if the number of data points on this surface is greater than \( n_{\text{min}} \), or

\[
\left[ \frac{\omega_{rr} \left( \tan^{-1}\left( \frac{y_b + d}{x_b} \right) - \tan^{-1}\left( \frac{y_b}{x_b} \right) \right)}{\omega_p} \right] > n_{\text{min}}
\]

(3.8)

where \( n_{\text{min}} \) must be chosen through experimentation to ensure accurate data quality. If \( d < d_{\text{min}} \), and the given conditions are sufficient for the event to be considered observable (n > \( n_{\text{min}} \)), then a tailgating event is determined to have happened.

Given the specific goal of detecting semitrailers tailgating cars, the results can be further filtered to exclude events that occur when the following vehicle is a car. The
length of a semitrailer is much longer than a typical passenger vehicle, and that distance will be reflected in a larger distance $y_{ab}$ between points A and B, or

$$y_{ab} = r_b \sin(\theta_b) - r_a \sin(\theta_a)$$  \hspace{1cm} (3.9)

Distance $y_{ab}$ is demonstrated in Figure 3.5. Thus, tailgating events in which the following vehicle’s length $y_{ab}$ is less than that of a standard semitrailer can be ignored.

---

Figure 3.5: Diagram of vehicle locations showing calculated values: host vehicle (0), target lead vehicle (1), target follow vehicle (2)
Additionally, the algorithm must ensure that false-positives appear in no more than \( \alpha = 0.05 \) (5\%) of cases. To this end, the system performs the following statistics calculation after gathering data for one second. It is assumed that the calculated following distance, \( d \), follows a Gaussian distribution, and that distance readings are gathered at a rate of \( \omega_{rr} = 10\text{Hz} \). Therefore, at each one-second interval, \( N=10 \) samples will have been gathered. Furthermore, it is assumed that distance samples are random and have equal variance. A hypothesis test was devised to determine whether or not the measured value of \( d \) is greater than or equal to calculated minimum distance, \( d_{\text{min}} \), with 95\% confidence. The null and alternative hypotheses, \( H_0 \) and \( H_1 \), are given as

\[
H_0: \, d \geq d_{\text{min}} \quad (3.10)
\]
\[
H_1: \, d < d_{\text{min}}
\]

With a sample size of \( N=10 \), a single sample, one-tailed T test is the appropriate statistical tool, with 9 degrees of freedom (DOF). For each one-second population, the sample standard deviation must be calculated,

\[
\sigma = \sqrt{\frac{\sum_{i=1}^{N} (d_i - \bar{d})^2}{N-1}} \quad (3.11)
\]

where \( \bar{d} = \frac{\sum_{i=1}^{N} d_i}{N} \). The t-score is then calculated as

\[
t_{\text{calc}} = \frac{\bar{x} - d_{\text{min}}}{\frac{\sigma}{\sqrt{N}}} \quad (3.12)
\]

If \( |t_{\text{calc}}| > |t_{0.05,9}| \) then the null hypothesis \( H_0 \) must be rejected. In this case, for the most recent 1 second of data gathered by the system, it can be said that the vehicle
was tailgating with 95% confidence for the previous one second. This calculation is performed anew for each second of data that is gathered to determine if a vehicle has violated $d_{\text{min}}$.

III. OVERVIEW OF TAILGATING SYSTEM

For this preliminary system, three further assumptions are imposed to formulate the detection problem:

A2: All vehicles on the roadway are always visible
A3: Target vehicles of interest will be located in front of the host vehicle
A4: Target vehicles remain in the same lane

The proposed system consists of the following major components: a color camera mounted on a pedestal, a scanning laser range-finding sensor, a computer, and an interface through which the system can interact with systems already aboard the police vehicle. The laser range-finding sensor mounted on the roof of the vehicle, and scans the environment known angular velocity $\omega_p$. The sensor receives distance information at a known refresh rate $\omega_{rr}$ and transmits this data to the processor. The processor analyzes each $\theta=360^\circ$ sweep, using the data gathered to form an understanding of the vehicle’s surroundings. As the system is only interested in target vehicles located in front of the host vehicle, only the first 180$^\circ$ of rotation are considered. Using absolute velocity information gathered from the host vehicle, the system calculates an appropriate following distance $d_{\text{min}}$ for all vehicles in the immediate area. In addition to the
previously mentioned statistical approach to determine if \( d < d_{\text{min}} \), a penalty function is employed to further reduce the likelihood of false positives. For each instant that the system statistically determines a vehicle is following by a distance less than \( d_{\text{min}} \), its penalty count is increased by a penalty function \( \kappa(d) \), defined by

\[
\kappa(d) = 1 - \ln \left( \frac{d}{\Gamma} \right)
\]

where \( d \) is the following distance, and \( \Gamma \) is a scaling factor used to adjust the severity of the function’s dependence on following distance.

For each instant that a tailgating event is not attributed to a vehicle, its penalty count decreases by a constant \( \kappa_{\text{dec}} \). If the penalty count for a specific vehicle exceeds the limit \( p_{\max} \), it is said to be tailgating, and the officer is notified. Environmental data recorded includes velocity, time, location, following distance, and a time history of the penalty function for the target vehicle. In this way, more than one vehicle may be detected simultaneously, and the system is resistant to noise or random errors signals. A flow chart illustrating the logic flow through the system is shown in Figure 3.6.
IV. Case Study

The proposed system was recreated in Matlab to verify the proof of concept. First, a three-dimensional environment variable was created and populated with specified vehicles. The first two dimensions (x, y) were spatial, the third dimension (t) was time. In this way, each vehicle of specified length was placed into a lane, and moved through the
environment in each time step according to its specified velocity relative to the host vehicle. This environmental variable was then analyzed in such a way to approximate the operation of the proposed system. At each time step, the environment was scanned in the x and y dimensions for the presence of a vehicle. If a vehicle was detected, it was given an ID and its location relative to the host vehicle was calculated (absolute distance $r$, and angle $\theta$). Once each vehicle was detected, their locations were translated into x and y coordinates, as the proposed system would, and the following distance between inline vehicle pairs at each time step was calculated using basic geometry. Using the logic discussed previously, a penalty function was applied against vehicles which were found to be in violation of the minimum following distance $d_{\text{min}}$. A number of cases were simulated. The parameters listed in Table 3.2 were used for every simulation.

Table 3.2: System tuning parameter values used in simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{\text{min}}$</td>
<td>20</td>
<td>m</td>
</tr>
<tr>
<td>$n_{\text{min}}$</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>$p_{\text{max}}$</td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>$v_{\text{host}}$</td>
<td>60</td>
<td>kph</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>200</td>
<td>-</td>
</tr>
<tr>
<td>$\kappa_{\text{dec}}$</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

A. Two-Vehicle Simulations

The simulation was configured to represent two vehicles progressing down a roadway. First, the vehicles were placed far enough apart so that they were not tailgating.
The initial vehicle conditions for this simulation are listed in Table 3.3. The penalty against each vehicle is shown as a function of time in Figure 3.7. A plot of the simulated laser data at an instant in time is shown in Figure 3.8. Since no tailgating occurs, the penalty function shows zero for the duration of the simulation.

Table 3.3: Initial conditions for vehicle tailgating simulation, in which no tailgating occurs.

<table>
<thead>
<tr>
<th>Vehicle No.</th>
<th>Initial Lateral Position (x)</th>
<th>Initial Longitudinal Position (y)</th>
<th>Vehicle Length</th>
<th>Velocity Relative To Host</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10m</td>
<td>20m</td>
<td>10m</td>
<td>0 m/s</td>
</tr>
<tr>
<td>2</td>
<td>10m</td>
<td>45m</td>
<td>5m</td>
<td>5 m/s</td>
</tr>
</tbody>
</table>

Figure 3.7: Penalty function for two-vehicle scenario in which no tailgating occurs
The second case examined was that in which the semitrailer was tailgating the lead vehicle for a short period of time. The conditions for this scenario are shown in Table 3.4. The penalty against each vehicle is shown as a function of time in Figure 3.9. A plot of the simulated laser data at an instant in time is shown in Figure 3.10. Vehicle 1 is shown tailgating Vehicle 2 for a short period of time, which causes an increase in the penalty function. Since Vehicle 2’s velocity is higher than that of Vehicle 1, its following distance $d$ exceeds $d_{\text{min}}$ at approximately 1 second, after which the penalty function decreases back to zero. By comparing Figure 3.8 with Figure 3.10, the difference in following distance may be observed by comparing the distances between Vehicles 1 and 2.
Table 3.4: Initial conditions for second simulated scenario, in which tailgating occurs for a limited time.

<table>
<thead>
<tr>
<th>Vehicle No.</th>
<th>Initial Lateral Position (x)</th>
<th>Initial Longitudinal Position (y)</th>
<th>Vehicle Length</th>
<th>Velocity Relative To Host</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10m</td>
<td>20m</td>
<td>10m</td>
<td>0 m/s</td>
</tr>
<tr>
<td>2</td>
<td>10m</td>
<td>35m</td>
<td>5m</td>
<td>5 m/s</td>
</tr>
</tbody>
</table>

Figure 3.9: Penalty function for two-vehicle scenario in which vehicle 1 tailgates the lead vehicle for approximately 1 second
The third case examined was that in which Vehicle 1 was following Vehicle two at a distance closer than $d_{\text{min}}$ for a period of time long enough to exceed the tailgating penalty limit $p_{\text{max}}$. The conditions for this scenario are shown in Table 3.5. The penalty against each vehicle is shown as a function of time in Figure 3.11. A plot of the simulated laser data at an instant in time is shown in Figure 3.12. In this case, even though the velocity of Vehicle 1 was higher than that of Vehicle 2, it was not high enough for Vehicle 1 to increase its following distance to greater than $d_{\text{min}}$ before exceeding the penalty threshold $p_{\text{max}}$. Therefore, Vehicle 2 was guilty of tailgating. As before, comparing Figure 3.12 and 3.10 illustrates that Vehicle 1 is following Vehicle 2 more closely.
Table 3.5: Initial conditions for second simulated scenario, in which tailgating occurs.

<table>
<thead>
<tr>
<th>Vehicle No.</th>
<th>Initial Lateral Position (x)</th>
<th>Initial Longitudinal Position (y)</th>
<th>Vehicle Length</th>
<th>Velocity Relative To Host</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10m</td>
<td>20m</td>
<td>10m</td>
<td>0 m/s</td>
</tr>
<tr>
<td>2</td>
<td>10m</td>
<td>31m</td>
<td>5m</td>
<td>3 m/s</td>
</tr>
</tbody>
</table>

Figure 3.11: Penalty function for two-vehicle scenario in which vehicle 1 tailgates the lead vehicle for approximately 1 second.
Figure 3.12: Numerical response of the laser range reading vs. scan angle for a semitrailer following a passenger vehicle at velocity and initial separation distance listed in Table 3.5

B. Three-Vehicle Simulations

Additional simulations were performed using three vehicles instead of two. The first scenario is one in which a tractor trailer (Vehicle 1) follows two passenger vehicles (Vehicles 2 and 3). At no time during this simulation does any tailgating occur, as seen in Figure 3.13. The laser readout of this simulation just after the initial condition is shown in Figure 3.14. The initial conditions for this scenario are shown in Table 3.6.
Table 3.6: Initial conditions for simulated three-vehicle scenario, no tailgating occurs

<table>
<thead>
<tr>
<th>Vehicle No.</th>
<th>Initial Lateral Position (x)</th>
<th>Initial Longitudinal Position (y)</th>
<th>Vehicle Length</th>
<th>Velocity Relative To Host</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10m</td>
<td>20m</td>
<td>10m</td>
<td>0 m/s</td>
</tr>
<tr>
<td>2</td>
<td>10m</td>
<td>45m</td>
<td>5m</td>
<td>5 m/s</td>
</tr>
<tr>
<td>3</td>
<td>10m</td>
<td>76m</td>
<td>5m</td>
<td>5 m/s</td>
</tr>
</tbody>
</table>

Figure 3.13: Penalty function for three-vehicle scenario in which no tailgating occurs
Figure 3.14: Numerical response of the laser range reading vs. scan angle for a semitrailer following two passenger vehicles at velocity and initial separation distance listed in Table 3.6

The second three-vehicle scenario examined was that in which Vehicle 1 was tailgating Vehicle 2 for a period of time, and Vehicle 2 was tailgating Vehicle 3 for a time sufficient to exceed the penalty threshold. The conditions for this scenario are shown in Table 3.7. As shown in Figure 3.15, the tailgating penalty function increases more severely for Vehicle 2 than for Vehicle 1. This is because the following distance is closer initially. Additionally, this distance continues to be close for much longer as a result of the smaller relative difference in the velocities of Vehicles 2 and 3 compared to Vehicles 1 and 2. In this scenario, Vehicle 2 is guilty of tailgating while Vehicle 1 is not. The laser reading for the initial condition is shown in Figure 3.16.
Table 3.7: Initial conditions for three-vehicle simulated scenario, in which Vehicle 1 follows too closely and Vehicle 2 tailgates

<table>
<thead>
<tr>
<th>Vehicle No.</th>
<th>Initial Lateral Position (x)</th>
<th>Initial Longitudinal Position (y)</th>
<th>Vehicle Length</th>
<th>Velocity Relative To Host</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10m</td>
<td>20m</td>
<td>10m</td>
<td>0 m/s</td>
</tr>
<tr>
<td>2</td>
<td>10m</td>
<td>35m</td>
<td>5m</td>
<td>5 m/s</td>
</tr>
<tr>
<td>3</td>
<td>10m</td>
<td>50m</td>
<td>5m</td>
<td>8 m/s</td>
</tr>
</tbody>
</table>

Figure 3.15: Penalty function for two-vehicle scenario in which vehicle 1 tailgates the lead vehicle for approximately 1 second
Figure 3.16: Numerical response of the laser range reading vs. scan angle for a semitrailer following two passenger vehicles at velocity and initial separation distance listed in Table 3.7

C. Additional Scenarios

In addition to the cases examined here, it is worthwhile to discuss other possible scenarios. The case in which a trailing truck’s distance to the car in front of it varies sinusoidally may represent a truck traversing hilly terrain behind a passenger vehicle. In this case, the penalty function would increase as the truck got closer on the downhill section, and decrease after it fell behind on the uphill sections. However, the truck would only be guilty of tailgating if it stayed in the violation zone (i.e. \( d < d_{\text{min}} \)) long enough to exceed the penalty threshold \( p_{\text{max}} \).

Another case worth examining is that in which the host vehicle is traveling in the leftmost lane of a three-lane highway, and the target vehicle is in the middle lane. Since
the system makes both range and angle measurements relative to the host vehicle, it is able to calculate both the lateral and longitudinal distance from the host vehicle to all detected vehicles. Therefore, it can distinguish between a vehicle in the middle lane and a vehicle in the rightmost lane. This information reduces the possibility of incorrectly assessing a tailgating penalty against a vehicle in one lane that is near another vehicle in the next lane.

V. SUMMARY

The system proposed in this chapter allows a mobile law enforcement officer to continually monitor the state of traffic around him. It uses commercially available laser range finding technology in conjunction with novel processing algorithms to reliably determine when a vehicle is tailgating. The system uses a statistical approach to reduce the number of false positives in addition to allowing some flexibility in the visibility of the target. In the future, the system may be expanded to track multiple vehicle pairs simultaneously, in addition to tracking vehicles behind the officer. The data gathered by the system may be used to provide additional insight, including which areas are most prone to tailgating, vehicle classification and velocity statistics, following distance and more. A numerical model of the system was created and the fundamental concepts behind the system proved viable. If realized, this system affords law enforcement the ability to detect when vehicles are following too closely, and records data that can later be used for prosecution in court.
CHAPTER FOUR

CONCLUDING REMARKS AND FURTHER RESEARCH

This chapter provides closing remarks with regards to the materials discussed in this thesis. It summarizes the background information required, in addition to the advances made, the systems proposed, and the results obtained. Following this, five future areas of research are discussed in detail.

I. SUMMARY OF DISCUSSION

In this document, two tailgating detection systems have been discussed to aid law enforcement officers in detecting and documenting tailgating occurrences. The problem of tailgating was discussed as it pertains to causing crashes with resulting injuries and fatalities. Possible sources and solutions were discussed, with emphasis placed on enforcement of safe driving laws. Particular attention was paid to the role of tractor trailers in severe crashes where tailgating was a factor, due to the higher likelihood of fatalities in such incidents. First, a stationary system was proposed that continuously monitors traffic in a single lane of traffic for dangerous driving activities such as tailgating. Unlawful events are detected and recorded; the data may then be provided to law enforcement for prosecution purposes. A numerical simulation was developed in MATLAB to examine the validity of the proposed detection algorithm. Simulated vehicles were able to be accurately detected at velocities of up to 50m/s (112mph) for a passenger vehicle of nominal length. Additionally, a scale prototype was developed and tested to further investigate the concepts outlined previously. The prototype system,
based on commercially available microcontroller technology and inexpensive ultrasonic sensors, successfully detected the presence and velocity of a scale vehicle.

A mobile system was subsequently developed that scans the environment for tailgating drivers and notifies the officer of violators. The proposed system employs a laser range finding sensor to detect vehicles in the surrounding environment. A statistical method was devised to reduce the likelihood of false positives. A penalty function was discussed to allow for changing environmental conditions such as lane change events or varying target speed. A simulation was developed in MATLAB to investigate the soundness of the algorithm discussed. Results were obtained for a number of scenarios, including multiple vehicles traveling at differing speeds. In all cases, the vehicles were successfully identified and a tailgating penalty was appropriately assessed. Overall, this tool grants law enforcement and other government agencies the ability to penalize dangerous drivers, encouraging safer driving habits.

II. Future Work

At the conclusion of this project, five main areas of further work were identified to bring the discussed theories to maturity.

A. Full-Scale Hardware Prototype for the Stationary Tailgating Detection System

A complete, full-scale hardware implementation of the stationary tailgating detection system discussed in Chapter 2 should be developed and tested to further validate the proposed algorithm. The system should be designed using accurate laser range finding sensors, as opposed to the inexpensive ultrasonic range finding sensor used
in the scale test. In addition, the Arduino system should be adapted to store information permanently, using an SD card for example. Further, a means should be developed to enable recording video or pictographic evidence. Finally, a radio system should be implemented to allow the system to communicate with nearby officers when violators are detected. The system should be subjected to a small-scale field test at first work out any bugs in the hardware or software. Full size automobiles should be used in this test, which may be performed in a controlled environment such as a parking lot. The number of test runs performed should be sufficient to obtain statistically meaningful results regarding the system’s accuracy.

B. Full-Scale Hardware Prototype for the Mobile Tailgating Detection System

The mobile tailgating system discussed in Chapter Three should be realized as a complete working prototype. The system should use a commercially available laser range finding scanner, such as those developed by SICK AG. Initially, data processing could be done in LabView or similar PC-based data acquisition system. Eventually, a standalone hardware system should be developed to gather and process traffic data. A suitable camera that can be mounted on the exterior of the police vehicle and controlled by the detection system should be identified and implemented. Once the hardware system has been developed, a small scale field test should be performed. As with the stationary tailgating detection system, this test should be performed in a closed environment such as a large parking lot, with enough tests to obtain statistically significant results. Once the hardware and software bugs have been solved, a full field study should be performed.
C. Full-Scale Field Study of the Stationary and Mobile Tailgating Detection Systems

An appropriate field study should be performed with participation from various local and national law enforcement agencies to further develop the systems and advertise their capabilities. As the state highway police are the most likely to use the systems for tailgating enforcement, they should be the first group contacted. The systems’ abilities to detect and report tailgating should be advertised, as well as the ability to continuously monitor road use – including traffic conditions, average speed, number of cars, etc. Both systems should be tested on real roadways if possible. The stationary system should be mounted to an overpass for an extended period of time to gather and process data. The mobile solution ought to be installed on an actual police vehicle, and used on a number of public roads. Officer impressions and feedback should be taken into account for future development. Continued development of the hardware and software components of the system should occur to improve the user experience and system reliability.

D. Commercialization of Both Systems

Once the fundamentals of both systems have matured, they should be developed into refined, contained prototype systems ready for commercialization. This includes designing and implementing an enclosure for both devices to ensure proper protection against the elements. In addition to providing protection and convenience, a well-designed enclosure improves aesthetic appeal. A power supply should be designed for the stationary system that will allow it to collect data autonomously for at least a full 8 hours. The mobile system should be incorporated into a police vehicle’s existing technology package to ease use. In addition to these technical details, consideration should be given
to the possibility of branding both devices to better market them to law enforcement agencies. Full documentation on how to build and operate both systems should be completed. At this point, it would also be prudent to begin marketing the system to potential manufacturers. A price range should be identified for both systems, and an effort made to build interest amongst law enforcement agencies.

E. Work with Trucking Companies to Further Address Tailgating Issue

Finally, contact with various trucking companies should be established to further curb dangerous tailgating behavior. One possibility is to consider the inclusion built-in tailgating warnings for trucks. The technology used in both systems may be used to design a system that, when mounted to a tractor trailer, can self-report following distance to nearby law enforcement. This system could notify the driver of a violation in minimum following distance, physically enforce a reduction in speed, or broadcast this information to nearby patrol vehicles. This would provide an immediate punishment for truck drivers who tailgate, as opposed to the currently perceived minimal risk of a crash. Furthermore, a greater emphasis on safe following practices should be made in commercial license coursework and examination to ensure that ignorance is not a viable excuse. Finally, consideration should be given to modifying speed limits for trucks, as requiring them to drive 5-10kph (3-6 mph) slower than regular traffic would further reduce the likelihood of tailgating.
I. APPENDIX A: ARDUINO CODE FOR HARDWARE PROTOTYPE

This program, written for an Arduino, uses the NewPing library to continuously measure the distance reported by two ultrasonic sensors. A car is detected by sensing the change in detected distance. Once a vehicle is detected in the first sensor, a timer is begun. The time it takes for the vehicle to travel from one sensor to the next is used to calculate the vehicle’s velocity. After determining velocity, an appropriate following “time gap” is determined, during which no vehicle may enter without triggering the “tailgating detected” light. A diagram showing the logic of the prototype system programming is shown in Figure A.1. In addition, an illustrative wiring diagram for the prototype system has been provided in Figure A.2, with a technical schematic shown in Figure A.3.
Figure A.1: Pseudocode flow chart for Arduino prototype system
Figure A.2: A connection diagram for the prototype system using an Arduino micro controller
Figure A.3: A wiring schematic for the prototype stationary detection system

```cpp
// StationaryPrototypeSystem.ino
// Arduino Program to Measure vehicle Location and Speed
// By Tyler Zellmer

// Include the library designed for the ultrasonic sensors
#include <NewPing.h>

// Define pins for sensor 1
#define TRIGGER_PIN1  3 // Arduino pin tied to trigger pin on the ultrasonic sensor.
#define ECHO_PIN1 2 // Arduino pin tied to echo pin on the ultrasonic sensor.
```
#define LED_PIN1  4  // LED that is illuminated when sensor 1 is active

// Define pins for sensor 2
#define TRIGGER_PIN2  11  // Arduino pin tied to trigger pin on the ultrasonic sensor.
#define ECHO_PIN2     10  // Arduino pin tied to echo pin on the ultrasonic sensor.
#define LED_PIN2      12  // LED that is illuminated when sensor 2 is active

// Define LED pins
#define CARPIN        6  // Is car present?
#define TIMEPIN       7  // Is timer running?
#define TAILPIN       8  // Has tailgating occurred?

#define MAX_DISTANCE 200  // Maximum distance we want to ping for (in centimeters). Maximum sensor distance is rated at 400-500cm.

#define MIN_CAR_HEIGHT 5  // Minimum deviation from standard distance measurement that trips sensor

// Call the NewPing classes so we have access to their methods
NewPing sonar1(TRIGGER_PIN1, ECHO_PIN1, MAX_DISTANCE);  // NewPing setup of pins and maximum distance.
NewPing sonar2(TRIGGER_PIN2, ECHO_PIN2, MAX_DISTANCE);  // NewPing setup of pins and maximum distance.
// Set initial variables
int activeSensor = 1; // Which sensor is initially active?
int carPresent = 0;   // Is there a car present
int tailgatingHappened = 0; // Has tailgating happened?

// Declare the timer variables, set them to zero
// Velocity timer
float vtimerStart;    // Time when velocity timer begun
float vtimerStop;     // Time when velocity timer ends
// Tailgating timer
float ttimerStart = 0; // Time when tailgating timer begins
float ttimerMin = 0;  // Minimum time that must pass for safe following distance
float timerTiming = 0; // The difference between the current time, and the time that the timer began

// Declare distance variables
float standardDistance = 0; // Baseline distance
float dist1; // Distance read by sensor 1
float dist2; // Distance read by sensor 2

// Dummy function to calculate minimum time gap based on distance (kappa(d) in paper)
float calcGap(float time) {
    return time*100;
}
// Functions to run when Arduino boots

void setup() {
    Serial.begin(115200); // Open serial monitor at 115200 baud to see ping results.

    // Declare a baseline distance, the deviation from which will indicate that a car has entered
    standardDistance = sonar1.ping() / US_ROUNDTRIP_CM - MIN_CAR_HEIGHT;

    // Assign output pins, whose function are described above
    pinMode(LED_PIN1, OUTPUT);
    digitalWrite(LED_PIN1, HIGH);
    pinMode(LED_PIN2, OUTPUT);
    pinMode(CARPIN, OUTPUT);
    pinMode(TIMEPIN, OUTPUT);
    pinMode(TAILPIN, OUTPUT);
}

// Commands to run continuously when Arduino is on

void loop() {

    // If tailgating has occurred, wait for five seconds before resetting the timers, LEDs and tailgating flag
    if (tailgatingHappened == 1) {
        delay(5000);
        timerStart = 0;
    }
ttimerMin = 0;
tailgatingHappened = 0;
digitalWrite(TAILPIN, LOW);
digitalWrite(TIMEPIN, LOW);
}

delay(50); // Wait 50ms between pings (about 20 pings/sec).
29ms should be the shortest delay between pings.

// Begin timing
float timeNow = millis();

// If we have previously started the tailgating timer, how much
time has elapsed since then?
if (ttimerStart > 0)
timerTiming = timeNow - ttimerStart;
else
timerTiming = 0;
/* Serial.print("Timer: ");
Serial.print(timerTiming);
Serial.print(" ttimerMin: ");
Serial.print(ttimerMin);
Serial.print("\r\n"); */
// If the time that has passed since the tailgating timer has begun
is greater than the minimum time that must pass for a following
vehicle,

// then reset the tailgating timer.
if (timerTiming > ttimerMin && ttimerMin > 0) {
    ttimerStart = 0;
    ttimerMin = 0;
    digitalWrite(TIMEPIN, LOW);
}

// If the first sensor is currently active, use it (default sensor)
if (activeSensor == 1) {
    // Calculate distance measured by sensor 1
    float uS1 = sonar1.ping(); // Send ping, get ping time in
    microseconds (uS).
    dist1 = (uS1 / US_ROUNDTRIP_CM);

    // If the distance is less than the baseline measurement, and
    we don't already know about this car...
    if (dist1 < standardDistance) {
        if (carPresent == 0) {
            vtimerStart = timeNow; // Begin the velocity timer
            activeSensor = 2; // Switch to sensor 2
            carPresent = 1; // Set the flag that a car is present
            digitalWrite(CARPIN, HIGH); // Illuminate the car LED
            digitalWrite(LED_PIN1, LOW); // Turn off the sensor
        }
digitalWrite(LED_PIN2, HIGH);  // Turn on the sensor 2 LED

delay(10);

}  // Otherwise, no car is present, and turn off the car LED

else {
    carPresent = 0;
    digitalWrite(CARPIN, LOW);
}

}  // If the second sensor is active (because sensor 1 has just
detected the leading bumper of a vehicle)

if (activeSensor == 2) {

    // Calculate the distance measured by sensor 2
    float uS2 = sonar2.ping();  // Send ping, get ping time in microseconds (uS).
    dist2 = uS2 / US_ROUNDTRIP_CM;

    // If the distance is less than the baseline measurement...
    if (dist2 < standardDistance) {
        // ... and the tailgating timer has already begin, and the required elapsed time hasn't passed ...
        if (timerTiming > 0 && timerTiming < ttimerMin) {

    }
// Reset the tailgating timers, and notify the world that tailgating has occurred!
ttimerStart = 0;
ttimerMin = 0;
tailgatingHappened = 1; // Set the tailgating flag
digitalWrite(TAILPIN, HIGH); // Illuminate the tailgating LED
}

// Calculate the velocity of the vehicle by calculating the difference between the current time, and the time when sensor 1 was tripped.
// Also, switch back to sensor 1 for the next loop
vtimerStop = timeNow;
activeSensor = 1;
float vtimeDiff = vtimerStop - vtimerStart;

// Calculate the minimum time which must pass before another vehicle may safely pass by the system
ttimerMin = calcGap(vtimeDiff);
ttimerStart = timeNow;
digitalWrite(TIMEPIN, HIGH); // Illuminate the timing LED
digitalWrite(LED_PIN2, LOW); // Turn off sensor 2's LED
digitalWrite(LED_PIN1, HIGH); // Turn on sensor 1's LED
Serial.print("Car took "); // Notify the user how fast the
car passed through both sensors (which can be used to calculate
velocity)

Serial.print(vtimeDiff);
Serial.print(" ms to cross both sensors. \n\r");
Serial.println(ttimerMin);

}
II. APPENDIX B: STATIONARY TAILGATING DETECTION NUMERICAL SIMULATION

This simulation creates a virtual environment containing a number of vehicles and two sensors. Once the environment is defined, all knowledge of the vehicles is gained from reading the two virtual sensors, to be as realistic as possible. The logic flow through the program is meant to simulate the logic shown in Figure B.1.

![Diagram](image)

Figure B.1: Logic flow through simulation of stationary tailgating detection system

%% Program To Simulate Mobile Tailgating Solution
clear;
clc;
close all;

%% Define The Simulation Environment
% Simulation length (seconds) and time step (seconds / step)
simulation_time = 4;
simulation_ts = 0.001;

% Resolution scaling factor (resolution = 1 m / scaling)
scaling = 100;

% Define the vehicles
% vehicle(id) = [x_start (m), length (m), velocity (m/s)]
vehicles{1} = [ 25 5 49];
vehicles{2} = [ 15 5 33.25 ];
%vehicles(3) = [ 5 5 25 ];

% Define the system location
% sensor = ["x" location (m), distance "d" between sensors (m)]
%    road     sensors  overpass
% |=============o o|          |=====|
% |<----- x ----->|
%            >|      |<-- d
sensor = [80, 1];

%% Perform Calculations on Sim Environment
% Make time space
time_space = 0:simulation_ts:simulation_time;
time_length = length(time_space);

% Scale variables
sensor = scaling.*sensor;
for i=1:length(vehicles)
    vehicles{i} = scaling.*vehicles{i};
end

% Create environmental variable
% environment (Time, X Position) = vehicle index
% Guess environment size using first vehicle's starting position and
% velocity
environment = zeros(time_length,vehicles{1}(1)+vehicles{1}(2)*simulation_time);
for t = 1:time_length
    for i = 1:length(vehicles)
        % Place the vehicle in the environment
        environment(t, round(vehicles{i}(1)+time_space(t)*vehicles{i}(3))) = i;
        % Give the vehicle length
for j = 2:vehicles{i}(2)
    environment(t, round((vehicles{i}(1)-j+1)+time_space(t)*vehicles{i}(3))) = i;
end
end
end

% Update environment size variable, after velocity-induced growth
[x y z] = size(environment)
(environment_size(1) environment_size(2)) = size(environment);

%% Detect Vehicles "Under" Scanner, and Time When They First Pass
% vehicles_detected = [vehicle id, time first detected]
vehicles_detected = 0;
vehicles_detected2 = 0;
sensor2 = sensor(1)+sensor(2);
k = 1;
j = 1;
for t=1:time_length
    % Detect vehicles under first sensor. Ignore duplicates (i.e. only one
    % record per vehicle, allowing for length of vehicle to pass under
    % sensor)
    if (environment(t,sensor(1)) > 0 & & any(environment(t,sensor(1)) ==
vehicles_detected(:,1)) == 0)
vehicles_detected(k,1) = environment(t,sensor(1));
vehicles_detected(k,2) = t;
k = k+1;
end

% Same logic for second sensor.
if (environment(t,sensor2(1)) > 0 && any(environment(t,sensor2(1)) == vehicles_detected2(:,1)) == 0)
vehicles_detected2(j,1) = environment(t,sensor2(1));
vehicles_detected2(j,2) = t;
j = j+1;
end
end
end

%% Calculate Vehicle Speed and Following Distances
[r, c] = size(vehicles_detected);
for i=1:r
% Calculate vehicle speed in m/s
vehicle_speed(i) = (sensor(2)/100)/(simulation_ts*(vehicles_detected2(i,2) - vehicles_detected(i,2)));
end

% Display vehicle speeds
format long
disp(vehicle_speed);
% Display time gap between each vehicle pair

if r>1
    for i=1:r-1
        vehicle_time_gap(i) = simulation_ts*(vehicles_detected(i+1,2) - vehicles_detected(i,2));
    end
end
This simulation creates a virtual environment containing a number of vehicles and a host vehicle. Once the environment is defined, all knowledge of the vehicles is gained from reading the data reported by the virtual range finding sensor, to be as realistic as possible. The logic flow through the program is meant to simulate the logic discussed in Chapter Three. The simulation is meant to approximate the logic of the actual system, shown in Figure C.1.

**Figure C.1:** Logic flow through proposed mobile tailgating solution
%% Program To Simulate Mobile Tailgating Solution
%% By Tyler Zellmer
%% March 5, 2013

clear;
cic;
close all;

%% Define The Simulation Environment
disp('Creating Environment...');
drawnow('update');

% Simulation length (seconds) and time step (seconds / step)
simulation_time = 4;
simulation_ts = 0.01;

% What is the tailgaing threshold?
tg_threshold = 5;

% Resolution scaling factor (resolution = 1 m / scaling)
scaling = 10;

% Define environmental size (square, m)
% Host vehicle is placed at (x,y) = ((environment_size/2), 0)
environment_size = 50;
host_location = [environment_size/2, 0];
% Define vehicle starting locations and velocities
% vehicles{index} = [x position, y position, length, velocity]
vehicles{1} = [40 20 10 0];
vehicles{2} = [40 35 5 5];
vehicles{3} = [40 50 5 8];

% What is the minimum following distance? (m)
minimum_following = 20;

% Make time space
time_space = 0:simulation_ts:simulation_time;
time_length = length(time_space);

% Scale variables
environment_size = environment_size*scaling;
host_location = host_location*scaling;
minimum_following = minimum_following*scaling;
for i=1:length(vehicles)
    vehicles{i} = scaling.*vehicles{i};
end

% Create environmental variable
% environment (X position, Y position, Time) = vehicle index
% Note: The environment will grow in the Y direction if a vehicle's
% velocity causes it to move outside of the original size.
environment = zeros(environment_size);
for t = 1:time_length
    for i = 1:length(vehicles)
        % Place the vehicle in the environment with velocity
        environment(vehicles{i}(1),
        vehicles{i}(2)+round((time_space(t))*vehicles{i}(4)), t) = i;
        % Give the vehicle length
        for j = 2:vehicles{i}(3)
            environment(vehicles{i}(1), (vehicles{i}(2)-
            j+1)+round((time_space(t))*vehicles{i}(4)), t) = i;
        end
    end
end

% Update environment size variable, after velocity-induced growth
% [x y z] = size(environment)
[environment_size(1) environment_size(2) environment_size(3)] =
size(environment);

% Place a border wall to conform with assumptions made in paper. Make
% "vehicle id" = -1.
environment(environment_size(1),:,:) = -1;

% Scan Environment for Vehicle Locations
disp('Scanning Environment for Vehicles...');
drawnow('update');

% Pretend we don't know each vehicle location (as in real life) and
% scan
% the environment array for vehicles. If a vehicles is found, report
% the
% angle and distance to vehicle, as would be reported by the laser.
% Also
% record its ID (which vehicle has been detected).
% theta{id} = [theta, vehicle id]
% r{id} = [r, vehicle id]

% For all time
%theta = cell(environment_size(1)*environment_size(2),time_length);
%r = cell(environment_size(1)*environment_size(2),time_length);
for t=1:time_length
    k=1;
    % For every x location
    for x = 1:environment_size(1)
        % For every y location
        for y = 1:environment_size(2)
            % If a vehicle is found, record its location and identity
            if (environment(x,y,t) ~= 0)
                theta{k, t} = [atan((y-host_location(2))/(x-host_location(1))) environment(x,y,t)];
                r{k, t} = [sqrt((y-host_location(2))^2+(x-host_location(1))^2) environment(x,y,t)];
            end
        end
    end
end
% Keep things in the positive theta
if theta{k, t}(1) <= 0
    theta{k, t}(1) = theta{k, t}(1) + pi;
end

k=k+1;
end
end
end

%% Calculate Vehicle Locations
disp('Calculating Vehicle Locations...');
drawnow('update');

% vehicle_loc(assigned vehicle id, time) = [x location, y location, original vehicle id]
% vehicle_length(assigned vehicle id) = vehicle length
for t=1:time_length
    k=1;
    last_vehicle = 0;
    for i=1:length(r)
        % If the vehicle ID is > 0 (i.e. if it is a real vehicle)
        if r{i,t}(2) > 0
            % Identify the x,y location of each vehicle's front bumper
            (only
% one per vehicle)
if last_vehicle ~= r{i,t}(2)
    vehicle_loc{k,t} = [r{i,t}(1) * cos(theta{i,t}(1)),
                  r{i,t}(1) * sin(theta{i,t}(1)), r{i,t}(2)];
    last_vehicle = r{i,t}(2);
    vehicle_length(k) = 1;
    k=k+1;
    % Calculate the length of each vehicle
else
    vehicle_length(k-1) = vehicle_length(k-1) + 1;
end
end
end
end

%% Calculate Following Distance for Inline Cars

disp('Calculating Following Distances...');
drawnow('update');

vehicle_count = k-1;
% following_distance(vehicle id,
for t=1:time_length
    % For each vehicle that's been detected
    for i=1:vehicle_count
        l=1;

for j = 1:vehicle_count
    % Compare against every other vehicle that's been detected.
    if
        % they are in the same lane, and are not the same car,
        compare
            % the distance between them.
        if (j ~= i && round(vehicle_loc{j,t}(1)) ==
              round(vehicle_loc{i,t}(1)))
            following_distance(vehicle_loc{i,t}(3), l, t) =
                round(vehicle_loc{j,t}(2)) - round(vehicle_length(j)) -
                round(vehicle_loc{i,t}(2));
            l=l+1;
        end
    end
end

%% Make Tailgating Determination

% penalty_count(vehicle id, time) = cumulative count
penalty_count = zeros(vehicle_count, time_length+1);
for t=1:time_length
    % For every vehicle in every time step
    for i = 1:vehicle_count
        tailgating = 0;
        % Compare following distance of each vehicle to the minimum,
% while ignoring duplicates (A --> B and B --> A distances are
% in
% the following_distance variable, but we only need one of
them)
% If tailgating occurs between our i'th vehicle and any other,
set
% variable to 1
for j = 1:l-1
    if following_distance(i,j,t) <= minimum_following &&
    following_distance(i,j,t) > 0
        tailgating = 1;
    end
end
% If tailgating was detected, penalize. If not, and our penalty
% function is greater than zero, reduce it by one.
if tailgating == 1
    penalty_count(i,t+1) =
    penalty_count(i,t)+distancePenalty(following_distance(i,j,t),scaling);
elseif penalty_count(i,t) > 0
    penalty_count(i,t+1) = penalty_count(i,t)-1;
end
end

%% Plot R vs Theta values
disp('Creating Plot...');
drawnow('update');
% Number of animation frames
frames = 2;
figure(1);
A = moviein(frames);
set(gca, 'NextPlot', 'replacechildren');
m=1;

% Create plots for each time frame
% for t=1
for t=1:round(time_length/frames):time_length
    figure(1)
    clf;
    hold on;
    % Draw each vehicle and point in the environment
    for i = 1:length(r)
        if (r(i,t)(2) ~= 0)
            plot(theta(i,t)(1),r(i,t)(1)/scaling,
                 '.')
        end
    end
    xlabel('Laser Angle, \theta (rad)');
    ylabel('Laser Reading, r (m)');
    axis([0 pi/2 0 100]);
    A(:,m)=getframe(gcf);
    %disp(environment(:,t,t));
    m=m+1;
end
%% Create GIF

movie2gif(A,'MobileSolution.gif');

%% Plot penalty count

figure;

plot_type = ['-r'; '--g'; '-*b'; '-o'; '-vm'];
hold on;
for i=1:vehicle_count

plot(time_space,penalty_count(i,1:time_length),plot_type(i,1:3),'linewi
dth',2);

    legends{i} = ['Vehicle ' num2str(i)];
end
legend(legends,'location','northwest');
hold off;
xlabel('Time (s)');
ylabel('Penalty Count');
title('Penalty Count for All Vehicles');
IV. Appendix D: Penalty Assessment MATLAB Code

This code is called by the mobile vehicle simulation code displayed in Appendix C to determine a distance-based penalty for vehicle tailgating. It is equivalent to the function $\kappa(d)$ discussed in the text.

% Function is called by mobile tailgating detection simulation to penalize vehicles that are tailgating too closely.

function out = distancePenalty(dist, scale)

    % Output (penalty) is a mathematical function, as described in the paper

    out = 1 - log(dist / (20 * scale));
REFERENCES


