BrakeSafe:
An Intelligent Assisted Reversal System

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Abstract

Elderly drivers face a number of cognitive, physical and sensory deficiencies which make it more difficult for the aged to safely operate a vehicle. One area of particular difficulty for elderly drivers is safely reversing a vehicle, where the driver is at increased risk of colliding with obstacles obscured by the vehicle's blind spots. To assist elderly drivers with slow reaction times and poor peripheral vision, it is proposed that an assistive driving system, henceforth referred to as the "BrakeSafe system", be developed to take autonomous preventative action to avoid automotive collisions while reversing.

Interviews were conducted with users in the target demographic, as well as experts in the fields of automotive sales and cognitive ergonomics and a list of product requirements was produced. Among this list, the most import requirements were: "The system accurate identifies collision risks," "the system can be easily disabled," and "the system requires minimal user intervention to operate." Accompanying these requirements, a series of metrics were selected to help judge the effectiveness of the concepts being generated; these metrics include: vehicle stopping ability, maximum safe reversal velocity, false positive rate, accessibility of user controls and the number of steps required for a user to activate the system.

The BrakeSafe system can be decomposed into three functional units: sensing, processing and action. The sensing function is performed by a rear-facing array of sonar sensors used to detect stationary and moving objects in a 240° arc behind the vehicle. An embedded computer is responsible for interpreting the data received from the sensors according to a number of pre-programmed heuristics measuring velocity and proximity. As well, this embedded computer is responsible for interfacing with the mechanical braking apparatus—a pneumatic piston cylinder which engages the vehicles brakes by applying a 900N downward force to the vehicle's brake pedal. Mathematical simulations indicate that this braking appartatus can decelerate a vehicle travelling at speeds of 50 km/h *in under 2 seconds.*

Initial performance of the BrakeSafe prototype is extremely promising; in a series of trials conducted with the prototype installed in an actual vehicle, the system was able to accurately identify and avoid collisions with both moving and stationary pedestrian obstacles with a very high rate of success. The final cost of both the prototype and final product were under $400. This is less than the cost of vehicular damage in a moderate collision, indicating the economic feasiblity of the BrakeSafe system. Recommendations for future development include: improving the system's user interface to provide more useful feedback to the driver, implementing a "diagnostic" system to help identify potential system failures, and reducing the physical footprint so as not to interfere with the normal operation of a vehicle's pedals.

1 Introduction

1.1 Assistive Driving and The Elderly

With the impending retirement of the baby boomers, Canada's elderly population—i.e. persons who are of age 65 or older— is poised to experience rapid growth. Canada's elderly population is currently growing by approximately 2–3% each year; at this rate, it is estimated that over 21% of Canada's population will be classified as elderly by 2026. [1] As well, the majority of elderly persons in Canada live independently in their respective communities and have expressed wishes to remain independent. [2] Given the rapid growth of Canada's aged population and this demographic's desire for autonomy and independence, there is a strong need for new services and systems to address the unique needs of Canada's burgeoning elderly population.

Travelling by automobile is an important part of life for many North Americans, irrespective of age. In North America, elderly persons are more likely to hold a valid license and to operate a vehicle than elderly persons 20 years ago. Due to the increase in "aging in place" and the proliferation of low-density, car-friendly suburbs, many elderly persons are likely to face severe mobility losses without the means to safely operate a vehicle, hampering one's ability to interact in one's community and prohibiting elderly persons from accessing goods and services. [3]

Safely operating a vehicle is a difficult task, requiring fast reflexes and a high degree of situational awareness to identify and avoid potential hazards, as well, operating a modern vehicle requires a high degree of mental overhead, often requiring an operator to use several controls in parallel while executing complex maneuvers. Operating a car while reversing is exceptionally difficult, as an operator must contend with large blind spots, requiring frequent shoulder checking and sharp peripheral vision. The large blind spots present on many large vehicles make it difficult for drivers to locate obstacles directly behind a vehicle, exposing both the driver and bystanders to considerable risk. [4]

While all drivers are hampered by these large blind spots, elderly drivers are at particular risk for collisions with unseen obstacles. [5] Older drivers are impaired by a number of physical, cognitive and sensory deficiencies resulting in poor peripheral vision, slow reaction times, poor dexterity and decreased flexibility in the neck and upper body. [6] These impairments contribute to an increased risk of colliding with objects while reversing, necessitating an assitive driving solution to aide elderly drivers with controlling a reversing vehicle. Augmenting an elderly driver's ability to identify and react to hazards while operating a vehicle will serve to reduce the risk accidents for both bystanders and elderly drivers.

1.2 State of the Art

Preexisting reversal assistance systems fall under two broad categories: 1. passive systems, which attempt to improving the driver's field of view, reducing the size of the vehicle's blind spots, and; 2. active systems, which provide additional information about objects in the vehicle's blind spots to the driver by means of electronic sensors. While both of these approaches to reversal assistance are currently deployed in commercial available vehicles, neither approach adequately addresses the physical and cognitive impairments which afflict elderly drivers.

Passive systems such as convex mirrors and rear-facing cameras are the most simple of the reversal assistance systems currently available. These systems address reversal assistance problems by augmenting the user's field of view, effectively reducing the size of a vehicle's blind spots and enabling a driver to see behind the vehicle without moving one's head. The relative simplicity of these systems make them both low cost and easy to retrofit onto older vehicles. However, provide a number of potential distractions to the user by requiring the driver to split his/her attention between multiple "view ports" while reversing and are incapable of compensating for a driver's slow reaction times, inattentiveness or other driver errors.

Active systems employ arrays of proximity sensors to provide drivers with addition information about potential obstacles behind a vehicle. These systems are capable of detecting stationary and moving obstacles and relay information—namely the proximity to other objects— back to the driver through either an audible or visual user interface installed in the vehicle. These systems carry the possibility of overwhelming the user with additional information, preventing the driver from being able to make a clear, accurate decisions while reversing, which could in turn reduce the driver's ability to correctly respond to an environmental hazard.

None of these pre-existing solutions are adequate in addressing the needs of elderly drivers. In order to adequately address the needs of elderly drivers, a new system must be developed, specifically designed for this target demographic.

2 Problem Statement

The elderly have slower reaction times and reduced mobility, making it difficult for an elderly driver to identify and respond to obstacles behind one's vehicle. While reversing, a vehicle should take preventative actions to avoid collisions with both stationary and moving obstacles in the event that the driver is unaware of said obstacles or incapable of reacting in a timely manner.

It has been established that there is a considerable risk of collision to all drivers who are reversing their vehicles. [4] However, the elderly are a demographic which is at particular risk to this problem area due to their slow reaction times. [7] Accordingly, there is a need for a product which can either identify or improve the response time to external events which require sudden braking while reversing. While a number of pre-existing products assist drivers in identifying obstacles which may lie or may cross the path of the vehicle—both when the vehicle is reversing and moving forward—these pre-existing systems fail to address the slow reaction times of certain users, such as the elderly. In the event that the user is unable to react quickly enough, an ideal system should slow or stop the vehicle, reducing the likelihood of a collision.

3 Customer Needs & Product Requirements

Once a problem has been identified, the next step is to figure out what the users see as a solution. This entails creating a list of various customer needs. This was done by the group, and these needs were translated in terms of the language of the product. The following needs were gathered from a diverse set of sources. Interviews were conducted with both members of the target demographic —i.e. elderly persons— and experts in relevant fields, including cognitive ergonomics and automotive sales. These interviews were very beneficial when deriving user needs, and knowledge was gained about the current state of the art, the target demographic, and the causes of the collisions that the design team was trying to solve.

3.1 Product Requirements

The information obtained from conducting interviews was translated into needs statements which were in turn used to generate a series of requirements expressed in the language of the product. These requirements are later employed to to evaluate the feasibility of potential solutions developed during the "concept generation" phase of the product design process. One statement of particular interest is "Once the snow banks get really tall, shoulder checking for oncoming traffic is pretty much impossible." This statement, phrased in the language of the product, is "The system accurately identifies collision risks." Meeting this need is paramount to success of the project, as a system which cannot detect a collision certainly cannot avoid one.

Another statement of particular interest to the design team was "There must be a way to turn off the system for the people who have trailers." This concern was expressed again and again by our customers: the ability to turn off the system easily, at a moment's notice. This statement was translated to "The system can be easily disabled", which became a major design criteria for the both the final system and the prototype.

One statement which really struck the design team was “Sounds great! Will it work on my old car?”. If the system is to remain economically feasible it must be able to be installed in pre-existing vehicles, as some members of the target market do not wish to purchase a new vehicle. Thus, an ideal system is one which is interoperable with old cars. This statement was translated into the need “The system maintains effectiveness when used on a variety of vehicles.”

“[Older drivers] have difficulty with multi-tasking. They have problems with complex environments that require rapid response.” First, it outlines one of the major contributors to elderly accidents difficulty with processing information in parallel. This indicates the need for a system which can act autonomously, as a user may either be too unfocused or too confused to provide the system to engage. When the system engages, it should do so while distracting the current driver as little as possible. This statement was translated to “The system requires minimal user interaction to operate.”

The above statements and many more were gathered from the aforementioned target demographic and experts, on topics ranging from weather conditions, to how the environment data is gathered, to installation costs. These statements each generated one or several product requirements.

3.2 Metrics

Now that the product has requirements that it must meet, it is necessary to design metrics such that the team can figure out just how well some system meets those requirements. These metrics must be quantifiable, so that each and every system can be objectively judged, and the best system chosen in the end. As with the product requirements, much of the work to design these metrics have been previously published by the design group. Because of this, it would be extremely inefficient to attempt to reproduce that work, so it will be given here verbatim. Thus, below in Table 1 of the myriad metrics that were developed by the group in order to objectively measure the various systems generated in the concept generation stage. Note that this table contains metrics for all of the product requirements developed by the group, not just those that are given above.

Once again it is important to note that many of the metrics deal with safety, either directly or indirectly. Thus, it should be evident to the reader that safety of the users is a primary concern on the design team, and every effort to ensure it was taken.

3.3 Needs in the Final Prototype

Following the construction and testing of the BrakeSafe prototype, user needs were compared against the prototype’s functionality to determine how well the system satisfied the needs collected from potential users.

Let’s start with the major needs of the product, as identified in the above subsections. “The system accurately identifies collision risks.” It is difficult to answer whether or not this need was met, since the prototype was built essentially as a proof on concept. For all the tests that were run on the prototype, the system performed at least as well as expected when identifying potential hazards, and sometimes acted before the design team had anticipated.

The requirement that the system can be easily disabled was certainly met. A large disable button was mounted on the steering wheel, which when depressed would fully disengage the system. Another requirement that was met with a full success was the ability to install the system in pre-existing vehicles. The final prototype was installed on an old car, without having to interface or interfere with any of the car’s internal workings or controls. The final major customer need, regarding the system requiring minimal user interaction to operate, was also considered a success for the group. The prototype, in its current form, engages fully automatically, without any user intervention. This is one of the features which sets this system apart from others of its kind: the ability to act autonomously to prevent collisions.

Several user needs were not adequately addressed by the current BrakeSafe prototype. For example, the need for providing audible feedback to the user when the system is engaged. This was viewed as a secondary need for demonstrating the core functionality of the system, but for any production model of the system this requirement would have to be met. As well,

Table 1. Table of Metrics [8]

#	Need	Metric	Importance	Units
1	2	Stops Vehicle	5	binary
2	2	Maximum Reversal Velocity	4	km/h
3	2, 3	Maximum Direct Object Velocity	3	km/h
4	4	Maximum Acceleration on User	5	m^2/s
5	1, 3	Minimum projected area to detect objects	4	cm^2
6	3, 10	False Positive Rate	4	%
7	1, 3, 10	False Negative Rate	5	%
8	7, 9	System remains responsive	5	binary
9	9	Time for system response to user input	3	s
10	11	Mechanism to Discourage User Complacence	3	binary
11	4, 10	No action when action would cause collision	5	binary
12	5, 6, 10	Under failure, car operation is unaffected	5	binary
13	6, 10	User notified of system failure	4	binary
14	15	No Protrusions on Vehicle	2	binary
15	10, 15	Radiation emitted	2	mSv
16	5	Maximum voltage to run	2	V
17	5	Maximum Power Usage of System	2	W
18	5, 12	Does not affect other systems	3	binary
19	7, 16	Mass	1	kg
20	12	System not affected by other systems	3	binary
21	1, 17	Maximum effective rainfall intensity	4	mm/hr
22	1, 17	Maximum effective snowfall intensity	4	cm/hr
23	1, 17	Detection still passes in fog	3	binary
24	17	Resists damage from environment	2	binary
25	1, 17	Works in all light range	2	binary
26	14	Time between warning user and action	4	s
27	14	Maximum noise emitted	3	dB
28	14	Maximum light intensity	1	binary
29	2, 17	Minimum co-efficient of friction [ice]	2	N/N
30	2, 17	Minimum co-efficient of friction [wet asphalt]	2	N/N
31	8, 10	Mean time before failure	2	months
32	7, 9	Accessibility of disable mechanism	4	m
33	8	Cost of new system	4	$
34	8	Cost of retro-fitted system	3	$
35	7, 16	New actions user must learn	2	# actions
36	7, 16	Steps to performs action	3	# steps
37	7, 16	Controls are easy for all age groups	4	binary

no testing was performed to ensure that the system would work in a variety of weather conditions; it is predicted that the ultrasonic sensors will fail when exposed to precipitation due to inadequate weatherproofing of the sensor enclosures. Finally, from an ergonomic standpoint, the system currently lacks functionality to discourage user complacency. Again, this was viewed as secondary compared to displaying the core concept of the system; however, to ensure the long term safety of the users this feature would need to be implemented in a final product.

Of course, if this system were ever implemented on the large scale, many of the prototype features would have to change, and thus the fulfillment of the design requirements would have to be re-evaluated. For instance, the sensors would have to work in variety of conditions and for a long period of time in order for the system to be considered safe at all. However, whether or not the system would work on old cars, for instance, could be dramatically affected by what form the final design took. It is conceivable that the only non-instrusive way to deploy the system would be as part of the vehicle's drive-by-wire system, in which case it would be nearly impossible to install on old cars. Thus, while most of the needs were met for the prototype, a full re-evaluation of those needs would be required if the design were to change in any significant way.

4 Concept Generation, Selection & Testing

A number of concepts were generated for each major product requirement The concepts, addressing functionally related requirements, were then evaluated against each other using decision matrices. Finally, a system comprising all of the individual components was considered and presented to users who indirectly evaluated the choices via verbal walk-throughs and questionnaires.

4.1 Identification of Hazards

The accurate and reliable identification of potential hazards is one of the most important functions of the system. Two types of information must be known for the system to make correct decisions. First, it must be able to detect and track external objects such as pedestrians or other vehicles. Second, it must know key information about the vehicles movement, such as speed and the degree of turning, which can be used to identify and ignore harmless, stationary, objects.

4.1.1 External Object Sensors

Various types of distance and proximity sensors were considered for detecting external hazards. Using the selection criteria of cost, detection distance, detection reliability, environmental tolerance, resolution and accuracy, and coverage area, infrared, magnetic, optical/visual and laser sensors were all determined to be ill suited to the needs of the system.

Radar based sensors were found to be the optimal choice. Ultrasonic sonar sensors were also found to be an acceptable choice, suffering mainly from reduced detection distance but benefiting from significantly reduced cost.

4.1.2 Vehicle Sensing

As mentioned, it is important for various statistics, such as speed and turning angle, to be known for the system to make informed decisions about when to act and what inputs, received via the external object sensors, represent legitimate hazards.

Some information may be provided by the vehicles on-board computer via the OBD-II protocol, specifically vehicle speed but no standard exists to access turning information [9]. Various sensors were therefore examined which would be able to detect turning information. High resolution encoders mounted on opposite wheels, accelerometers, gyroscopes and surface tracking systems similar to those used in optical mice were considered.

A gyroscopic sensor would likely be more accurate than other options to measure turning with some units having a drift of only 0.1 degrees per second [10] which would be more than sufficient for the application. Despite the statistics found for some sensor types, none of the possible options was determined to be significantly better or worse than the others with the limited information available regarding the characteristics of a vehicle. It was concluded that more information, research and testing would be required before any solution could be concluded best. Such a limitation was deemed acceptable since the choice of sensors used to detect turning or speed measurement would have little to no discernable impact on the user or proof of concept prototype.

4.1.3 Sensor Placement

The placement of the external sensors used to detect hazards affects the performance of the system and its ability to reliably detect objects. Various factors were used to evaluate possible mounting locations including the possibility of interference from expected objects, aesthetics and isolation from harsh conditions.

Considering sensor placements, four locations are possible as shown in Figure 1. Generally, sensors mounted higher such as those on the roof or trunk (1 and 2) are less susceptible to interference and exist in a cleaner environment but are also more visible and thus less aesthetically appealing. Although hidden, those mounted lower, either on the bumper or underneath the vehicle (3 and 4), are more likely to experience interference or be damaged or impaired due to the harsher environmental conditions. After weighing the options using a decision matrix, sensors mounted at bumper level were found to be most promising.

4.2 Mechanism to Disable the System

As discussed, an important product requirement was the ability to disable the system quickly and easily. After brainstorming while sitting in the vehicle, three different options were considered, a button placed on the steering wheel, a button placed on the dashboard and a voice recognition mechanism. By evaluating against the criteria of false negative rate, cost, accessibility and response time to user input, a button mounted on the steering wheel was found to be the most promising candidate. This choice is primarily driven by the reduced accessibility of a button mounted on the dashboard, particularly when looking behind the vehicle and the high false negative and response time of any voice recognition system.

4.3 Applying Brakes and Stopping the Vehicle

Another integral part of the system is the activation of the brakes. The best way to activate the brakes would be electronically by interfacing with the cars on-board computer. This would avoid the need for additional mechanical parts but would limit the system to new vehicles only. The standardized vehicle communication protocol in use today, OBD-II [9] does not support any control of the vehicle and would therefore be poorly suited. Additionally, most cars still use the traditional hydraulic control system [11].

The use of pneumatic and electric actuators was considered, each of which would physically depress the brake pedal. When evaluated using the criteria of response time, installation simplicity and cost, electric actuators were deemed to be the most effective despite their high price [12].

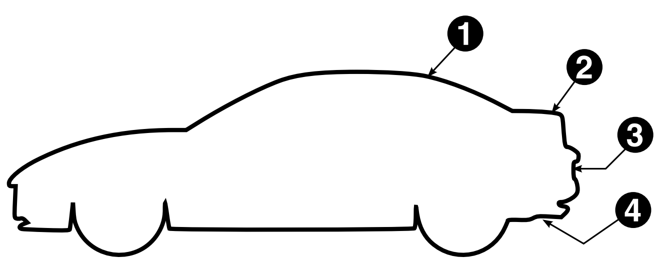

Figure 1. Sensor Mounting Locations: Side View

4.4 Concept Testing

Having identified a system comprised of each choice made previous, users were asked to evaluate the design. Feedback was sought for the operation of the system as a whole and the choices made to satisfy specific requirements. Users were asked to participate in verbal walk-throughs for given situations. They were also asked to answer more specific questionnaires.

4.4.1 Verbal Walk-through

Two important situations were described, along with other more specific scenarios, and users were asked to describe their reaction. The first involved a parked car which would not allow the driver to begin reversing since hazards had been detected. The second included the car stopping, while reversing, when hazards were detected at the operating distance of the chosen sensors. In each case for nearly all users interviewed, reactions were desired and expected.

4.4.2 Questionnaires

In addition to a verbal walk-through. Users were also given a questionnaire which focused on specific aspects of the system, specifically their reaction to automatic brake pedal depression, the disable button, and system cost which relates to nearly every aspect of the product. From these questionnaires, it was found users felt that a moving brake pedal would be confusing without some other form of feed back but that the placement of the disable button satisfied all of their needs. It was also found that the price of the system wold be acceptable, particularly if children were in the area.

4.4.3 Testing Results

After approaching users, possible improvements were brought to light, particularly related to user interaction and feedback. Despite these suggestions, users expressed confidence that the system would satisfy their needs.

5 Concept Prototype

5.1 Function

The BrakeSafe system can be decomposed into three functional sections: *Sensing*, which involves gathering data about the user, potential obstacles, and other environmental information; *Processing*, where the system takes the data acquired and performs analysis and decisions; *Action*, where the BrakeSafe system provides feedback to the user, and takes action to avoid potential collisions. Figure 2 demonstrates the BrakeSafe system's functional decomposition.

5.1.1 Functional Analysis

The sensing of the environment is performed by sonar sensors. In the prototype, four sensors are mounted on the rear of the vehicle. Two are located on the side of the vehicle in order to detect obstacles which may cross the pass of the vehicle as it is reversing, while the other two are located on the back of the vehicle in order to detect both moving and stationary obstacles directly in car's path.

An algorithm on a microcontroller determines if there is a collision with an obstacle imminent, and issues commands to take action. The sensor sets thresholds of acceptable proximities for both stationary and moving obstacles, and once a threshold is crossed the microcontroller engages the action process. For testing purposes, a user-interface was created and displays the data received by the sensors, as well as the respective levels of their thresholds. The user interface can be seen in Figure 3.

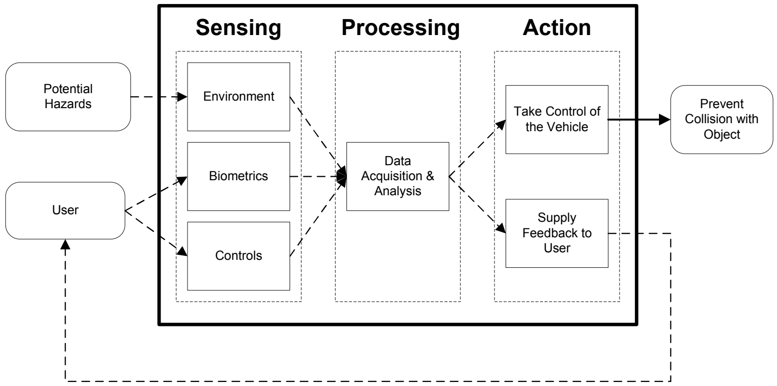

Figure 2. Function Diagram of the Reversal Assistance System

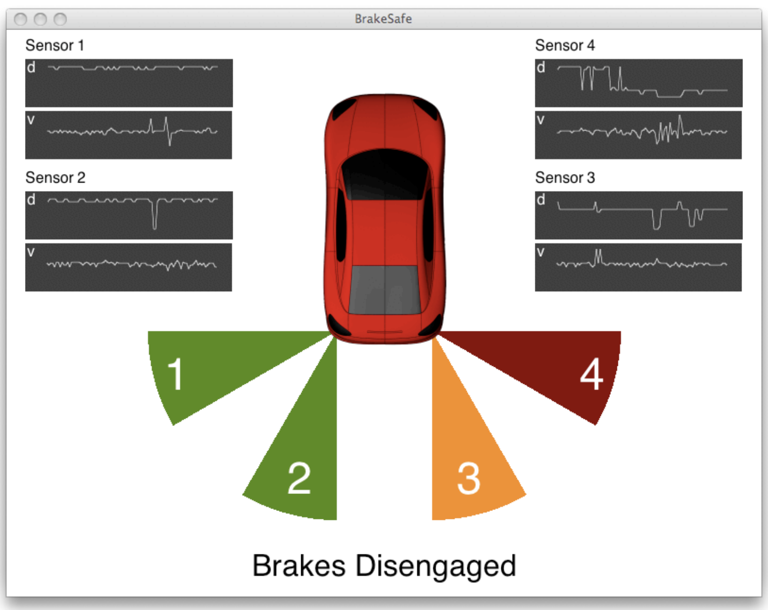

Figure 3. The BrakeSafe Monitoring Interface

The action process of the BrakeSafe prototype consists of a pneumatic actuator which depresses the vehicle's brake pedal. The actuator is mounted within a chassis and sits at the driver's feet. The microcontroller sends a signal to the solenoid of a valve, when then opens and causes the pneumatic actuator to compress. As the actuator is compressed, it pulls a cable attached to the vehicle's brake and causes the vehicle to stop.

5.1.2 Mathematical Modelling

A functional mathematical model of the BrakeSafe system was created prior to construction of the prototype. The Bond Graph modelling technique was used to characterize the brake pedal, and kinematic relationships were used to model the movement of the vehicle itself. The model takes as inputs parameters such as the vehicle's initial velocity and mass of the prototype car, and subsequently determines the amount of time in which the system can safely bring the vehicle to a stop. A description of the model parameters can be seen in Table 2.

Table 2. Model Parameters

t	time (s)
v	velocity (m/s)
v_{init}	initial velocity (m/s)
d_{stop}	displacement after system engages (m)
$g = 9.8$	acceleration due to gravity (m/s^2)
$m = 1260$	approximate mass of prototype car (kg)
$mu = 0.2$	coefficient of static friction
$F_{act} = 900$	force supplied by actuator (N)
$k_b = 8000$	spring constant of brake (N/m)
$d_b = 0.05$	maximum pedal displacement (m)
$G_b = 20$	gain of brake

The following state equations are derived from the system's bond graph, and are used to derive the differential equations which describe the system:

$$\dot{p_2} = \frac{R_4}{m}(p_2) + k_b(x_3) + F_{act}\dot{x_3} = \frac{1}{m}(p_2)$$

$$\begin{bmatrix} \dot{p_2} \\ \dot{x_3} \end{bmatrix} = \begin{bmatrix} \frac{R_4}{m} & k_b \\ \frac{1}{m} & 0 \end{bmatrix} \begin{bmatrix} p_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} F_{act} \\ 0 \end{bmatrix} \tag{1}$$

Using MATLAB computer simulation, predictions show that the actuator acts very quickly to apply force on the brake, to the extent that the force applied to the brake by the actuator can be modelled as a Heaviside function. This characterization is then applied to the kinematic relationships:

$$F(t) = (mu \cdot g \cdot m) + (G_b \cdot (F_{act} - (F_{act} - k_b \cdot d_b) \cdot u(t - 0.5)) \tag{2}$$

Such that:

$$v(t) = \frac{m \cdot v_{init} - \int_0^t F(t)\,dt}{m} \tag{3}$$

Equation 2 represents the total forces acting on the vehicle at time t, namely the coefficient of friction between the car and the ground, and the force which the brakes apply to the vehicle. The total time to stop the vehicle can then be found by using Equation 3, where t will be the time required to stop the vehicle—in other words, bring $v(t) = 0$. A simulation of the vehicle's velocity profile versus time can be seen in Figure 4.

The mathematical simulations show that the prototype vehicle can be brought to a stop in under 2.0 seconds for speeds under 50 km/h.

5.2 Form

As the prototype was created with the intent of demonstrating the functionality of the system, its form was largely a product of the prototype's intended function. The majority of the physical construction and form was in the chassis which held the pneumatic actuator, with a large portion of the prototype being in designing the microcontroller.

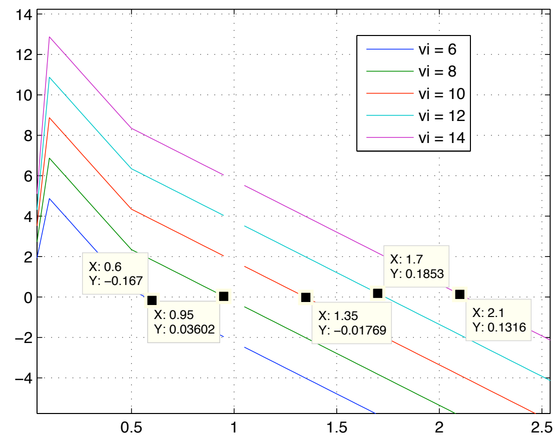

Figure 4. Velocity vs. Time as Initial Velocity Changes

5.2.1 3D Modelling

A 3D model of the BrakeSafe system was created prior to construction in order to finalize the form of the prototype. An isometric view of the chassis housing the acuator which depresses the brake pedal can be seen in Figure 5.

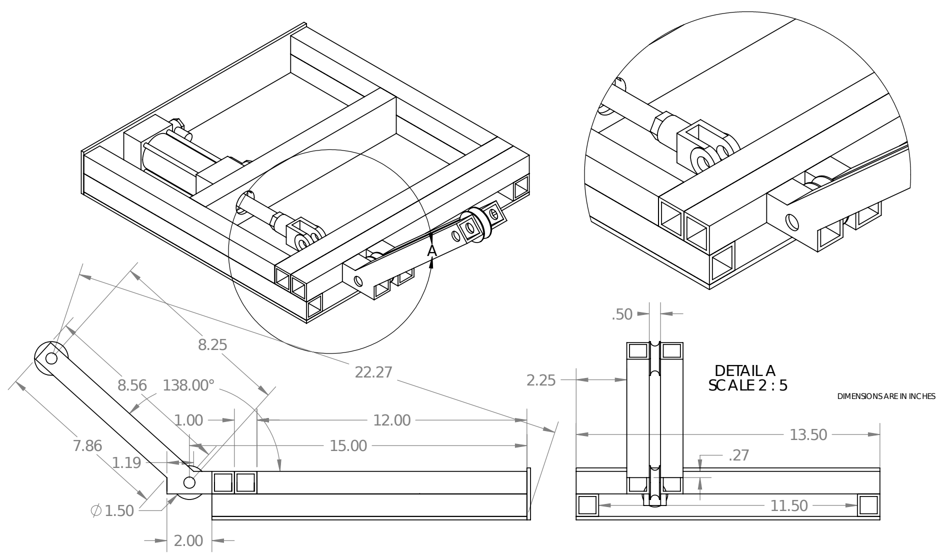

Figure 5. Construction Diagram

5.2.2 Construction and Material Used

The actuator chassis is made of steel square tubing, joined primarily using screws. The risers which guide and support the cable as it interfaces with the brake pedal needed to be mounted to the chassis at an angle, and needed to be welded in order to accomodate the size constraints of the car and the strength of the acuator. The welding was graciously done by the employees of the University of Waterloo's Engineering Machine Shop. The pneumatic actuator was powered by a compressed air tank which was located in the trunk of the prototype vehicle.

The microelectronics were assembled on a breadboard to allow for quick modification and debugging of the prototype circuit. The data from the sensors and microcontroller was monitored on a laptop, located in the passenger's seat of the prototype vehicle.

5.3 Feasibility

Moving from a proof-of-concept prototype to a production device requires that several questions be asked. It is important to address issues that may arise in scaling the prototype, challenges in the user interface, the cost of production as well as the feasibility of the environmental footprint of the product.

5.3.1 Prototype Scalability

While the prototype itself is fully functional, several important differences exist between it and a final production device. The differences are largely a reflection of the challenges and opportunities that come with mass producing a product. For example, the chassis that was custom engineered and fabricated to interface with the brake pedal of the prototype vehicle will not necessarily be appropriate for the vehicles of all end users. However, in light of this challenge, the opportunity of large-scale production would allow for the use of electric actuators—infeasible in the prototype due to high cost, but affordable as a final product due to economies of scale. A more full discussion of scaling the prototype to production level can be found in Section 6.3.

5.3.2 User Interface Issues

The prototype has been designed and implemented in order to show the feasibility of a system which can serve to address some of the dangers which may arise when reversing a vehicle. It has been designed from primarily a functional standpoint, and user interface issues which were not critical to the function of the proof of concept were beyond the scope of the prototype. A key issue to be addressed lies in ensuring that the user does not become complacent and eventually come to rely on the system—encouraging bad driving habits. An audible alarm can be used, similar to that in a seatbelt, to alert the user that the system has become engaged and annoy the user to discourage the user's desire to have the system engage. Further discussion of user interface issues is taken up in Section 6.3.

5.3.3 Economic Analysis

Determining the cost of producing a final design can be much more difficult than calculating the cost of a single prototype. Calculating the cost of production involves considering economies of scale, the efficiency of production, and other factors which can influence the final cost per unit produced.

The total cost of the final product is approximately $344, based on Aluminium Braking Frame - $30 (for materials and mass manufacture); High Powered Electric Actuators - $150; Micro computer - $60; Wiring (insulated copper wire throughout) - $2; Sensors - $90 for six high-precision sonar sensors; User Input - $2 for a button.

Table 3 shows the cost breakdown of both the prototype and final product by functional section. The cost of both the prototype and final product are less than the costs to repair the damage of moderate, victimless collision—making the BrakeSafe system and economically viable investment. Both the prototype and production costs also satisfy the total cost constraints.

Table 3. Approximate Cost Breakdown by Component

Function	*Prototype*	*Final Design*
Sensing	$100	$90
Processing	$16	$62
Action	$205	$170
User Feedback	$80	$2
Assembly and Install	Free	$50
Total	**$301**	**$344**

5.3.4 Environmental and Life-Cycle Analysis

The environmental impact of the product can be determined by using the energy consumption for each piece as a proxy for environmental damage. Based on energy production costs obtained from Industry Benchmark US Dept of Commerce EIO model from 1997 [13], the weighted energy use of each piece can be calculated, as shown in Table 4. The total cost of the energy use is then determined based on the data retrieved from eoilca.net [14]. The energy consumption breakdown of the BrakeSafe system is shown graphically in Figure 6

Table 4. Energy Usage Breakdown by Component

Piece	*Category*	*Weighted Energy Use in TJ/Mil USD97*
Frame	Aluminum extruded product manufacturing	1.75
Actuators	Fluid power cylinder and actuator manufacturing	3.14
Computer	Electronic computer manufacturing	0.78
Wiring	Copper wire, except mechanical, drawing	0.055
Sensors	Search, detection, and navigation instruments	0.98
User Input	Other computer peripheral equipment manufacturing	0.027
	Total:	6.73

6 Discussion

6.1 User Reaction

The user feedback from throughout the design process was both very positive about the design in general, and useful in refining the specifics. This is no different now that there is a working prototype. Upon seeing the video of the prototype in action, users were impressed with the working system. They feel it lends credibility to the design of the system, and that the

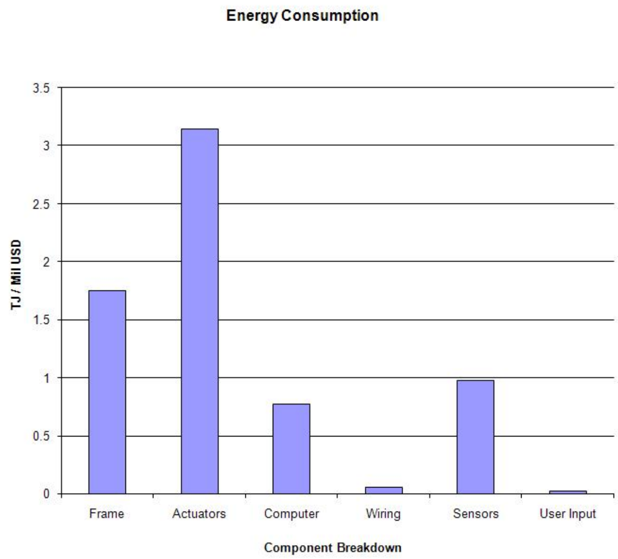

Figure 6. Energy Consumption Breakdown

behaviour displayed is very desirable. Comments such as "people will buy this" and "I wish my grandmother had one" were a common theme. In particular, users reacted very positively to a demonstration of the vehicle backing out of a parking stall, in which a pedestrian approaches behind a van, and the system stops the vehicle while the pedestrian is still out of sight of the driver. This is a situation with which many drivers can relate, and consequently resonates well with the potential users being surveyed. There was even positive feedback about the user friendliness of the system, which was encouraging considering the heavy focus this area had been given throughout the design process.

Unfortunately, due to the constraints of the demonstration exhibition, none of the users were able to experiment directly with the prototype. This does not stop them however from providing relevant criticisms of the prototype, which illustrate its shortcomings. Users were mostly concerned with the mechanical braking apparatus used in the prototype, particularly with regard to how it could get in the way of their feet, and whether it is safe. As well, users wished to know whether the system was capable of detecting small children, how the system would work in larger vehicles and at higher speeds, and how much a "shipping product" would cost. These comments are very useful in determining the direction of future development. The plans in the Future Recommendations section reflect the use feedback received.

6.2 Prototype Evaluation

The initial prototype was a resounding success, meeting or exceeding expectations in all areas of performance. In a series of trials, the system consistently detected person sized objects and brought the vehicle to a safe, controlled stop to avoid a potential collision. The test driver commented that in several trials the system engaged only moments before the driver was prepared to manually activate the vehicle's brakes. Additionally, the braking action taken was subjectively speaking very reasonable; because the system applies the brakes directly, the experience is not discernibly different from the actions of a human driver.

One reason the prototype worked so well was the iterative approach taken in developing the complex sensing and decision components. The prototype was implemented by first implementing only the most basic functionality—a single sensor using displacement detection—and gradually adding additional functionality once the basic functionality was verified to be operating as expected; this approach allowed the design team to progressively build an increasingly sophisticated system while being able to verify the system's correctness during each iteration.

Another design decision which contributed to the prototype's success was the over-engineering of the braking mechanism. The metal frame design chosen required much more time and effort to assemble than what might be necessary for a similar wooden or plastic frame, but provided a very solid and reliable base for the braking mechanism. The choice of pneumatic actuators also increased the size and complexity of the prototype, but ensured adequate braking force and quick actuation.

One difficulty with the prototype was the need to provide a demonstration of the system without a car in which to install the system. Because the prototype does not fit comfortably on a display table, it was difficult to convey both the broad purpose of the system and the specifics of the system's functionality. This shortcoming was somewhat mitigated by the use of appropriate aides including photographs of how the system mounts on the car and video footage of the system working.

6.3 Remaining Issues and Future Recommendations

Despite the satisfactory performance of the prototype, the BrakeSafe system remains primarily a proof of concept. There is substantial room for further design and improvement before the BrakeSafe system can reasonably become a commercially viable product.

The system's user interface (UI) requires a considerable amount of additional development before it can be deployed in a real vehicle. The UI accompanying the first prototype is mainly a debugging and display tool, and is not suitable for use in a production ready system. It is recommended that further and more formal user studies be conducted, and that several user interface mock-ups be prototyped and tested with users in the target demographic. One improvement that was heavily considered in the design phase but not fully represented in the prototype is an audible alarm, both to notify the user of system activation and help prevent user complacency. Another is the need to notify the user when the system is not functioning as it should—the equivalent of a "check engine" light.

The sensing and decision component of the system would also benefit from a second stage prototype. The number and types of sensors should be updated to more comprehensively cover the area behind the car; as well, a system prototype should be tested in a variety of situations and weather conditions, as much of this testing was precluded by tight time constraints when developing the initial prototype. Also, there is significant amount of work to be done in order to port the system's decision making algorithms from a hobbyist development development board to an equivalent platform suitable for mass production.

Moreover, the prototype's braking mechanism should be revisited in a second-stage of prototyping. The design used in the prototype adequately addressed the system's needs, but is infeasible for inclusion in a final design due to its size, placement, cost, and maintenance requirements. It would also be beneficial to provide a variable braking mechanism that could brake more firmly or gently depending on the specific situation. To accomplish these goals it is necessary to design a braking actuation component that integrates seamlessly with the braking systems on the cars in which it will be installed.

6.4 Conclusions

It is the unanimous opinion of the design team that overall the BrakeSafe project has proven a remarkable success. The successful demonstration of functionality by the prototype confirms that a computer assisted reversal system is practical, and the enthusiastic feedback from the users confirms that the system adequately addresses the needs of its target demographic. There is significant work which remains to be done to make the system production ready, both from a technical and user-centric standpoint. The prototype created is far from a finished product, but the fact remains that the problem of safe reversing is very real, and this project has shown that through careful design it can be solved.

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