Autonomous Braking

A Comparative Study of Human, Hybrid and Autonomous Braking Control for Cars

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1. Abstract

Road traffic injuries are currently one of the world’s leading causes of death. The subsequent costs to society are significant, both from an economic and a social standpoint, not to mention the significant emotional impacts. Human error plays a key role in a substantial proportion of motor vehicle accidents, creating a need to explore new ways to mitigate the safety risks posed by human drivers – even if this disrupts the status quo of human drivers.

This study uses a systems approach to analyse the impact of employing automatic braking systems (ABS) in cars – a system where the car uses sensors to identify hazards and automatically activates the brakes. It was found that removing humans from the car-braking control loop could more than halve the number of road accidents, leading to significant socioeconomic benefits, while also improving the efficiency and material lifetime of the brakes. The importance of the hybrid human-autonomous control case was also identified as a necessary step to improve human trust in autonomous technology.

2. Project Context – A Lethal Problem

Road traffic injuries are currently one of the world’s top ten leading causes of death (WHO, 2014) and are the leading cause of injury-related deaths globally (Zhang et al., 2012). In fact, it is the third-leading cause of deaths in China (GBD, 2014), causes an average of 11 deaths per 100 000 people in the USA (CDC, 2013) and accounts for ~25% of deaths among persons aged 15-24 in Australia (Risbey et al., 2010). A problem of such scale generates significant costs, with conservative estimates at ~1.7% of GDP for nations like Australia and the United States (BITRE, 2009) (Blincoe et al., 2015).

But what exactly are ‘road traffic injuries’? The World Health Organisation defines a road traffic injury as “a fatal or non-fatal injury incurred as a result of a collision on a public road involving at least one moving vehicle” (WHO, 2015). From this, we can see that the serious issue of road traffic injuries stems from vehicular collisions, with motor vehicles playing a role in the majority of injuries (GBD, 2014) (Wang et al., 2008) due to their much higher velocities increasing their hazard potential compared to pedestrians and cyclists. Thus, one of the most effective ways to reduce road traffic injuries, along with their associated socioeconomic costs, is through reducing motor vehicle accidents.

Human error plays a major role in a significant proportion of accidents, being a critical pre-crash event in 94%±2.2% of accidents studied in the National Motor Vehicle Crash Causation Survey conducted in the US (NHTSA, 2015) (NMVCCS, 2008). This data agrees with other findings where ~95% of accidents were attributed to human error from both drivers and pedestrians (Sabey & Taylor, 1980) and, more recently, data from the United Kingdom that found ~90% of road accidents could be attributed to human error on the part of either driver or pedestrian over the past four years from 2011 to 2014 (Dept. Transport, 2015). Other causes have a far less prominent role, with the next most significant being environmental factors such as road surface or defective traffic signals (<10%) and vehicle malfunction (~3%) (Dept. Transport, 2015) (NHTSA, 2015). Note that for the UK Dept. Transport dataset, multiple contributing factors were attributed to some accidents. In order to avoid
double counting, a conservative estimate of human-related contributing factors was made by assuming non-human factors like road surface were completely independent of human error. This was most likely an underestimate as factors like slippery roads were often paired with human errors like travelling too fast for conditions. Nonetheless, even with this underestimate, human error was still found to be a contributing factor in \( \sim 90\% \) of accidents.

3. Project Scope – Vehicle Brakes

There are two main ways to reduce the damage caused by motor vehicle accidents, thereby improving human safety – i) crash avoidance, and ii) crash protection (SafetyNet Project, 2009). The latter is concerned with minimising damage in the event of an accident, including technologies such as seatbelts and airbags. However, this is essentially a form of damage control that protects the highest priority element in the system – the human user, while failing to account for other damages such as vehicle damage and traffic congestion. Crash avoidance is a more preferable way to improve vehicle safety as it focusses on preventing the event of an accident altogether, thereby keeping people safe while also avoiding the other negative effects of motor accidents.

As already mentioned, human error plays a leading role in causing the serious problem of road injuries. According to the hierarchy of risk control (see Figure 1), a standard tool for assessing the effectiveness of risk control methods (Safe Work Australia, 2011), it is clear that the best-case solution would be to remove road traffic-related errors altogether. This is in line with Elimination-level solutions, which are the most reliable and provide the highest protection by completely removing the hazard from the system. However, this is an unrealistic target entailing perfect driving, perfect vehicle performance and perfect conditions.

Instead, noting the significance of human error in causing road accidents and the major role of motor vehicles in causing road injuries, the scope was narrowed to solutions based on control of the motor vehicle. Collisions occur when a vehicle’s motion takes it into contact with another road traffic element, whether it be another vehicle, a person, or an inanimate object. From the perspective of a driver controlling a vehicle, the main ways of avoiding this are either changing direction or stopping the vehicle through deceleration. This project chose to focus on the second option for the following reasons:

1. The probability of collision between two vehicles is reduced to zero if neither is moving whereas a steering vehicle can still collide with other objects on its new path.
2. *Stopping the vehicle is easier to implement as a solution based on steering would require all paths of all moving objects be considered to avoid collisions on the new path*

3. *Deceleration will reduce damage if a collision cannot be avoided, whereas changing direction will not necessarily decrease vehicle momentum and potential damage caused*

Having chosen to focus on collision avoidance based around controlling the vehicle’s ability to stop, it became logical to focus on the vehicle’s braking system.

4. **Braking Systems – Stopping Distances and Autonomous Braking**

Braking systems control the deceleration of a vehicle, meaning they have the potential to avoid collisions completely, while having the added benefit of reducing collision damage should one occur. One of the most important metrics used to measure the performance of a braking system (and the driver’s use of the system) is stopping distance, defined as:

*The sum of the distance travelled by the vehicle while the driver reacts and the distance travelled by the vehicle while decelerating to a stop.*

The second distance mentioned in the definition is the braking distance, and it depends largely on external factors beyond the project scope, such as road conditions, weather and the condition of the actual brakes. However, the reaction time is within the scope, relying on driver performance.

Despite being only on the order of a few seconds, the high velocities of motor vehicles means that even slight changes in reaction time can greatly affect stopping distance. For instance, using simple back-of-the-envelope estimation we find that for a car moving at 100km/h, one additional second required to react translates to nearly 30 additional metres travelled and increases impact velocity by ~23.4km/h (based on the typical deceleration for a car travelling at ~110km/h) (UK Govt, 2015). Calculations for the distance estimate are shown in Appendix A.

This means that human error can have a significant impact on the effectiveness of the braking system, with even slight mistakes meaning the difference between causing and avoiding a road accident. This has driven a number of leading car manufacturers such as Audi, Mercedes and Volvo to invest in the development of Advanced Emergency Braking Systems (AEBS) (ADAC, 2012), a new vehicle safety technology that operates by using sensors to monitor the environment and activates the brakes if a threat is imminent and the human driver doesn’t react (Thatcham, 2013). Referring back to the hierarchy of risk control (Figure 1), this solution operates at a substitution level (the most effective after elimination) by replacing the risk posed by human error with the risk posed by machine error.

5. **Man versus Machine – Safety Performance**

We explored this concept of autonomous braking further by comparing three methods of braking. Case 1 was the baseline case, based on the current-day situation with the brakes operated solely by humans. Case 2 was a situation where brakes are operated entirely autonomously, with no control
from the human driver. Case 3 considered a hybrid situation similar to the Google self-driving car where the vehicle operates in autonomous mode unless the driver activates a manual override (Google, 2015). These three cases are summarised in the control feedback systems below:

As discussed earlier, the performance of the safety system relies heavily on the reaction time to activate the vehicle’s brakes. Based on the control systems reaction time performance for each case was estimated (see Figures 5 to 7). Note that the braking time was not considered as this varies with vehicle velocity and the conditions of the road and brakes, all of which are independent of the brake controller and hence beyond the scope of this project. Furthermore, for Case 3 we assume the case where the human needs to manually override autonomous control. This is because this transition stage sets Case 3 apart from the other two – when it operates only in either human-controlled or autonomous mode it would simply behave like Cases 1 and 2 respectively.
Upper and lower reaction total reaction times, as well as distance travelled during the reaction time assuming a vehicular velocity of 100km/h (27.8m/s) for context, are summarised below:

Table 1 Summary of Total Reaction Times and Distance Travelled During Reaction Time (at 100km/h) for each Case

<table>
<thead>
<tr>
<th>Case #</th>
<th>Metric</th>
<th>1</th>
<th>s</th>
<th>2</th>
<th>s</th>
<th>3</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper Estimate</td>
<td>3.5</td>
<td>97.3</td>
<td>0.2</td>
<td>5.56</td>
<td>5.2</td>
<td>145</td>
</tr>
<tr>
<td></td>
<td>Lower Estimate</td>
<td>1.3</td>
<td>36.1</td>
<td>0.011</td>
<td>0.306</td>
<td>2.62</td>
<td>72.8</td>
</tr>
</tbody>
</table>

Note: For 2 cars travelling headlong at 100km/h, the distance travelled toward each other during the reaction time for the lower estimates of Case 1 and 3 are 72m and 145m, respectively, compared with just 11m for the upper (slower reaction) estimate of Case 2.

In terms of data reliability, it is reassuring to note that the brake reaction time for a human determined in Case 1 agrees with a number of studies that have established a 95th percentile reaction time of approximately 2.5 seconds (TRI OSU, 1997) (Taoka, 1989) (Sivak et al., 1982), with the unusually high upper estimate of 3.5 seconds for Case 1 taking into account external factors like driver fatigue and distraction rather than being a reflection of slower standard reaction times (NSW CRS, 2011). This more conservative upper estimate is preferable to help simulate realistic scenarios where drivers are under external influences that slow their reaction times beyond the normal distribution for standard human reaction times, such as drunk drivers.

From a time perspective, autonomous brake control (Case 2) significantly outperforms the other two cases, likely due to the significantly higher speeds of modern computers compared to human processing (Hars, 2010) (Eno, 2013). Case 1 is next best, while Case 3 performs surprisingly poorly. The reason for this is apparent in the feedback loop structure, with an additional step in Case 3 due to the process of the human driver reviewing the decision of the machine controller and deciding whether or not it is necessary to activate manual override.

Considering the best case for Case 3 (autonomous mode for hybrid) would perform the same as Case 2 while its worst case was worse than both Cases 1 and 2, it was not further analysed in the context of safety, socioeconomic cost or resource consumption. The decision to exclude Case 3 from the rest of the main study, along with its key role in the transition to autonomous vehicle technology, are further addressed in Section 8.

6. Saving Lives – A Socioeconomic Perspective

Clearly autonomous braking can reduce accidents and save lives. But by how much?

Based on US crash cause statistics (NHTSA, 2015), the following human errors were judged to be affected by a fully autonomous braking system:

- Driver inattention
- Driver fatigue
- Inadequate surveillance
- Misjudgement of speed and distance
Causes such as illegal manoeuvres and poor directional control were deemed to be outside the control of an autonomous braking system’s ability to avoid collisions. However, these causes still accounted for at least 55% of accidents (‘Other’ human errors, accounting for ~8%, were conservatively assumed to be outside the influence of autonomous braking systems).

The impact of autonomous braking in reducing the effect of these errors was determined by comparing braking controller reaction times with the time-to-collision (TTC) for motor vehicle accidents at a point 3 seconds before collision. The mean TTC was found to be 2.56s, with a minimum of 1.19s, while the mean TTC in near-crashes was 3.05s (Lee et al., 2007) which suggests that a reaction improved by 0.5s can convert a crash into a near-crash event, greatly reducing damage and cost. Comparing with the reaction times of Cases 1 and 2, we find that this means fully autonomous can virtually eliminate those accidents caused by the errors it can influence. This is because even the upper reaction time estimate of 0.2s for Case 2 allows for braking to be initiated more than 1s before the lower estimate of 1.3s for human drivers (Case 1) – an improvement almost double the 0.5s difference in TTC between a crash and near-crash event. Furthermore, the minimum TTC of 1.19s for crash events does not leave enough time for human reaction, with the lower estimate being 1.3s for Case 1. However, even the upper estimate for Case 2 would still allow braking to be initiated at a TTC of ~1s compared to no braking in Case 1 – a potentially lifesaving difference considering 0.5s can be the difference between a crash and near-crash. Based on mean TTC values we therefore find that fully autonomous braking virtually eliminates those accidents caused by errors it can influence, and so we assume it completely eliminates the accidents caused by these errors.

This reduced number of accidents using the autonomous braking system was then compared with US data from 2010 (Blincoe et al., 2015), representing the human-controlled baseline case.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Baseline 2010 USA</th>
<th>Fully Autonomous Brake Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of accidents (thousands)</td>
<td>13600</td>
<td>6057</td>
</tr>
<tr>
<td>Number of fatalities (thousands)</td>
<td>33</td>
<td>14</td>
</tr>
<tr>
<td>Number of non-fatal injuries (thousands)</td>
<td>3900</td>
<td>1737</td>
</tr>
<tr>
<td>Number of damaged vehicles (thousands)</td>
<td>24000</td>
<td>10689</td>
</tr>
<tr>
<td>Total Cost ($billion USD)</td>
<td>836</td>
<td>372</td>
</tr>
</tbody>
</table>

The data shows that the fully autonomous braking control is much better for human safety, likely more than halving the number of accidents and possibly having an even greater impact on reducing serious road injuries and fatalities. However, in order to achieve the full benefits of autonomous braking systems it is necessary for the public to first adopt this technology.

Cost is a significant barrier to the widespread use of autonomous vehicular control technology, including autonomous brake control. The main costs associated with the fully autonomous vehicle brake control system is the actual technology required to be fitted to the car. In fact, current devices like the Google self-driving car rely on a vast array of sensors to create a map of its surroundings (see
Figure 8) rather than relying on any external infrastructure (Undercoffler, 2014) (Guizzo, 2011). We therefore consider the upper and lower estimates of the costs associated with installing the technologies required for one autonomous vehicle, then scaled up to the number of light vehicles in the USA during 2010 as a baseline reference.

<table>
<thead>
<tr>
<th>Device</th>
<th>Lower Estimated Cost ($)</th>
<th>Upper Estimated Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central computer</td>
<td>295</td>
<td>29180</td>
</tr>
<tr>
<td>GPS</td>
<td>80</td>
<td>6000</td>
</tr>
<tr>
<td>Lidar (light detection and ranging)</td>
<td>90</td>
<td>8000</td>
</tr>
<tr>
<td>Odometry sensors</td>
<td>80</td>
<td>120</td>
</tr>
<tr>
<td>Radar sensors (short and long range)</td>
<td>175</td>
<td>250</td>
</tr>
<tr>
<td>Ultrasonic sensors</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Video cameras</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Total (1 car)</td>
<td>885</td>
<td>43770</td>
</tr>
<tr>
<td>Total (2010 LV fleet USA)*</td>
<td>204 billion</td>
<td>10087 billion</td>
</tr>
</tbody>
</table>

*2010 light vehicle fleet size was estimated at 230.4 million (BTS, 2013)

Note that in Table 3, the upper and lower estimates are quite extreme and that the upper and lower cost for one vehicle will likely lie closer to ~$10000 and ~$2000 respectively (BCG, 2015), which would bring total fleet cost estimates to ~$2 trillion USD upper and ~$460 billion lower. Nonetheless, the original estimates will be maintained to illustrate the full range of possible costs. In order to better understand the overall cost-benefits, the baseline case was compared with the upper and lower estimate scenarios for the fully autonomous case, taking into account the reduction in costs associated with the autonomous technology (see Table 4 below).

Note that the ‘Total Societal Cost of Accidents’ of $836b USD for 2010 was based on the figure for total value of societal harm from motor vehicle crashes in 2010 in the US determined by the NHTSA (Blincoe et al., 2015). This figure considered productivity and workplace losses, in addition to costs associated with medical, legal, emergency services, insurance administration and property/vehicle damage. Some costs were considered using necessary assumptions, such as lifetime economic cost society for each fatality ($1.4m USD), lifetime comprehensive cost (which includes economic and quality of life valuations) to society for each fatality ($9.1m USD), cost of medical services and lost productivity for critically injured survivor ($1.0m USD), and congestion costs being related to travel delay, increased fuel consumption and subsequent negative environmental impact. Note that the figure of $836b USD is a comprehensive cost figure – both economic and quality of life valuations were considered. Quality of life valuation was determined by considering aspects such as the physical
pain, impairment and emotional impacts that might reduce the quality of life for survivors (Blincoe et al., 2015). It should be noted that this methodology agrees with the road crash cost components identified by Risbey et al. in their approach to costing human losses (Risbey et al., 2010). The cost-benefit analysis also assumed the cost of the base vehicle excluding sensors would be constant for all scenarios, so this was not considered in the cost-benefit analysis below:

Table 4 Cost-Benefit Analysis of Autonomous Control versus Baseline, Considering Extreme and Moderate Versions of Upper and Lower Estimates

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Baseline</th>
<th>Autonomous Extreme Upper</th>
<th>Autonomous Upper</th>
<th>Autonomous Lower</th>
<th>Autonomous Extreme Lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Sensor Cost (2010 Light Vehicle fleet USA) ($b USD)*</td>
<td>0</td>
<td>10100</td>
<td>2304</td>
<td>461</td>
<td>204</td>
</tr>
<tr>
<td>Total Societal Cost of Accidents (Fleet) ($b USD)**</td>
<td>836</td>
<td>372</td>
<td>372</td>
<td>372</td>
<td>372</td>
</tr>
<tr>
<td>Net Comparative Cost (Fleet) ($b USD)</td>
<td>836</td>
<td>10472</td>
<td>2676</td>
<td>833</td>
<td>576</td>
</tr>
<tr>
<td>% of Baseline Cost</td>
<td>100</td>
<td>1250</td>
<td>320</td>
<td>99.6</td>
<td>69</td>
</tr>
<tr>
<td>Savings relative to baseline ($b USD)</td>
<td>0</td>
<td>-9636.35</td>
<td>-1840.35</td>
<td>2.65</td>
<td>259.65</td>
</tr>
</tbody>
</table>

*2010 light vehicle fleet size was estimated at 230.4 million (BTS, 2013); **Blincoe et al., 2015

From this result we can see that the extreme upper estimate has very low feasibility, increasing costs by an unsustainable amount (nearly $9 trillion, which would have accounted for two thirds of the US GDP of 14 trillion in 2010). However, we see that both lower estimates would reduce costs, with the moderate lower estimate doing slightly better than breaking even while the extreme lower estimate generates savings of ~$260b USD. From a purely financial perspective, it appears that adopting autonomous braking will likely increase overall net costs. However, four additional issues should be considered when looking at the cost of implementing autonomous braking.

Firstly, much of this technology is required for fully autonomous driving, meaning that on a longer term this investment can significantly reduce the investment required to achieve the higher levels of productivity and accident prevention afforded by fully autonomous vehicles.

Secondly, the technology costs will decrease over time, with systems such as autonomous valet parking and highway autopilot technology predicted to decrease to less than a third of introductory prices within ten years after introduction (BCG, 2015). This would reduce the moderate upper case to only $300b losses and would increase the savings in the moderate lower cost case to a significant $300b savings compared to the baseline.

Furthermore, this does not represent a yearly cost but rather an overall fleet analysis. Realistically, these costs will be spread over a number of years as they entire fleet will not instantly change to autonomous braking – it will instead be phased in, at best at the rate of new car sales, as this would mean every car sold that year had autonomous braking. Using an average of ~7 million new light
vehicles sold or leased (US Census, 2012), this translates to $292b and $55b in losses for the extreme and moderate upper cases, with the more realistic moderate $55b matching investments such as the US Government’s allocation to the Federal Emergency Management Agency. There has, however, been a decreasing trend in new car purchases/leases, with only 5.7 million in 2010 compared to over 9 million in 1990 (US Census, 2012), indicating potential over-supply that may slow down the phase-in of vehicles with autonomous braking systems.

Finally, it must also be remembered that these numerical cost benefits cannot quantify intangibles like the improved emotional condition from avoided collisions, meaning the savings listed above can be considered an ‘underestimate’ in that sense. In terms of ethics, this new ability to save a significant number of lives may be sufficient to precipitate a change in the status quo by permanently increasing overall investment in vehicle technology to continue to improve road safety.


Aside from the more well-known benefits regarding human safety, autonomous braking systems also have the potential to improve the efficiency of material and energy use.

In fact, the potential of autonomous braking to improve fuel efficiency for cars by 10-20% (Anderson et al., 2014) (Fagnant & Kockelman, 2014) is more significant than expected when considering braking losses only account for 5-7% of total vehicle energy losses (US Govt, 2015) (Consumer Energy Centre, 2015) (Bandivadekar et al., 2008). This seeming discrepancy can be explained by the fact there are multiple benefits rather than simply reducing wasteful braking, such as smoother acceleration/deceleration (Anderson et al., 2014) that can help avoid brake fade due to excessively high temperatures from sudden braking (Stephens, 2006) and reduced congestion as cars are able to stop closer to one another (Lari et al., 2014). These savings are significant, with a one percent improvement in fuel efficiency equating to over $4b USD in savings (Forrest & Konca, 2007). This indicates that a saving of even 10% would equate to ~$40b USD savings – offsetting ~70% of the annual $55b USD cost estimated for autonomous braking technology based on the moderate upper total sensor cost estimate. In terms of environmental impacts, this 10% improvement equates to a saving of 2.7% of the US’s total greenhouse gas emissions from 2013, this being ~180 million metric tonnes (EPA, 2014). Beyond the energy benefits, however, autonomous vehicles also have the potential to extend brake lifetime.

The materials audit and distribution of embodied energy for a standard braking system is below:

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
<th>Qty (kg)</th>
<th>Embodied Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brake Disc</td>
<td>Cast Iron</td>
<td>9.5</td>
<td>9.5kg × 25MJ/kg = 237.5MJ</td>
</tr>
<tr>
<td>Brake Pad</td>
<td>Ceramic</td>
<td>2</td>
<td>2kg × 20MJ/kg = 20MJ</td>
</tr>
<tr>
<td>Brake Piston</td>
<td>Stainless Steel</td>
<td>5</td>
<td>5kg × 56.70MJ/kg = 283.5MJ</td>
</tr>
<tr>
<td>Total Brake System</td>
<td>--</td>
<td>16.5</td>
<td>541MJ</td>
</tr>
</tbody>
</table>

*Data Source: (NREL, 2012) (Hammond & Jones, 2011)
From the Sankey diagram we can clearly see that in terms of embodied energy, the brake pad is by far the least significant. This indicates that in terms of saving energy, it is preferable to maximise the lifetimes of the piston and disc in comparison to the pad, as the pad has ~10 times less embodied energy meaning it is far more preferable as the replaceable part, though both the pad and disc generally require quite frequent changing due to wear though performance can vary between 40-100 thousand kilometres (AA, 2011). However, the most ideal situation would be to increase the lifetime of the entire system. It is generally believed that lifetime will be prolonged through improved braking efficiency by avoiding unnecessary acceleration and braking cycles and hence unnecessary wear of the braking system (Pyper, 2014) (Wang, 2015). However, it is also worth considering that autonomously controlled brakes may brake more frequently as they will stop at every legal requirement whereas humans can make judgement calls (though this decreases motor safety). Due to autonomous driving technology still being very new, very little literature was found regarding autonomous braking and material lifetime. An experiment is therefore proposed below to better understand the impact of human and autonomous driving on brake lifetime. This will hopefully assist in gauging environmental ramifications such as toxic waste and recycling difficulties linked to ceramics (metals like iron and steel are much easier to recycle) (Reuter et al., 2013) (EC, 2007) (Fenton, 1998).

We propose a case study of two fleets of 100 cars – one with autonomous brakes and the other with human drivers, with the fleet size based on a notable previous study into driver behaviour (Dingus et al., 2006).

- **Sample:** Car users/drivers will be selected from volunteers who declare that they frequently need to use passenger vehicles as a means of transport, with “frequently” defined as at least eight times a week (based four return trips to work).
- **Controlled Variables:** Geographic location will need to be controlled to within a city to try and control for climate and driving conditions/cultural attitudes (more aggressive drivers can cost 33% fuel efficiency (Karabasoglu & Michalek, 2013)).
- **Measured Variables:** Condition of the brakes, including material lost from brake components and change in brake effectiveness, will be assessed monthly for a year to account for all seasonal variations – weather alters road friction and hence brake use.
- **Comparative Study**: The condition of the brakes will be compared between autonomous and human drivers to develop an understanding of the impact of autonomous control on brake lifetime compared to the status quo of human drivers.

- **Additional Benefits**: Any brake repairs or replacements will be noted to develop an understanding of which brake components tend to wear the most severely.

8. Importance of the Hybrid Control Case (Case 3)

Case 3, the hybrid human-machine control case, was outperformed by Cases 1 and 2 in terms of reaction time and hence safety performance due to the presence of manual override. However, it should be remembered that the Case 3 time analysis only analysed the manual override situation unique to the hybrid case as a worst-case scenario reflecting human proneness to panic in urgent life-threatening situations, such as an imminent driving threat and subsequently overreacting to hazards or even perceiving non-existent threats (Hartley & Phelps, 2012) (Raghunathan & Pham, 1999).

In fact, it would be expected that the majority of time would be spent in autonomous mode (Google, 2015), meaning a safety performance similar to Case 2 could generally be expected. This suggests that Case 3 would generally be an improvement on the current real-world situation of Case 1. This is further exacerbated by people’s (often unfounded) mistrust of machine-based autonomous decision-making, such as algorithm aversion (Vedantam, 2015) (Dietvorst et al., 2014), which has been specifically profiled for autonomous vehicles in a comprehensive public opinion survey conducted in 2014 with respondents from the US, UK and Australia (Schoettle & Sivak, 2014). The qualitative data provided by the survey builds on findings by a number of other surveys that have found up to 88% of adults are uncomfortable with the idea of riding in an autonomous, driverless vehicle (Seapine, 2014) (Howard & Dai, 2013) (KPMG, 2013). Questions of interest in Schoettle & Sivak’s survey and graphical representations of qualitative data (quantified using simple count and percentage-based coding) are shown below. Note that although this survey considers fully self-driving cars rather than just self-braking, the findings below still illustrate highly relevant points about the degree of human trust in autonomous technology:

- **How concerned are about the following possible scenarios with completely self-driving vehicles (Level 4)?** (Note: Level 4 refers to fully autonomous vehicles requiring no human control during the journey)

![Figure 10 Graphical Representation of Quantified Coding of Qualitative Data from First Question of Interest (Schoettle & Sivak, 2014)](image-url)
This question is framed to generate qualitative data ranging from ‘Very concerned’ to ‘Not at all concerned’ for respondents regarding how concerned they are about different forms of transport being converted to self-driven. Notably, riding in a vehicle with no driver control is deemed the highest concern (average of ~80% either moderately or very concerned). This is interesting because it indicates people are most concerned about control of their private vehicles being relinquished – in other words, giving away control of the vehicle they most often drive themselves. It is also interesting to note that the question option is ‘Riding in a vehicle with no driver controls’. Generally people are happy to be passengers in a vehicle with a human driver, even though as a passenger they have no driving control, yet in the case of autonomous vehicles they become highly concerned. This may be due to respondents interpreting the question to mean riding when they would normally be driving, but it nonetheless shows that human unwillingness to trust self-driven cars is not only due to an unwillingness to give up personal driving control, but also due to a general mistrust of the ability of self-driving technology. The high concerns over commercial vehicles may again be due to phrasing of the response options, with the relevant option being ‘commercial vehicles such as trucks’. Whereas public transport is usually considered as something one rides in rather than a road obstacle, and taxis are generally smaller than trucks, this emphasis of trucks may have influenced respondents to view commercial vehicles as a hazard due to their larger size and subsequent dangers posed by trucks. This combined with a lack of faith in self-driving systems may have contributed to commercial vehicles being the second biggest point of concern (average ~78% moderately or very concerned).

- “If you were to ride in a completely self-driving vehicle (Level 4), what do you think you would use the extra time doing instead of driving?”

The use of the term ‘extra time’ for this question is interesting as it encourages the respondent to view this time as a form of spare time rather than travel time. This phrasing encourages the respondent to choose an alternative activity rather than watch the road, as this time is ‘extra’ as opposed to transport-related. Even more interestingly, despite this phrasing the option to watch the road was still the most commonly chosen at an average of 41%. This clearly suggests that people at present are still not willing to fully trust autonomous vehicles, instead opting to continue watching the road – double checking the machine controller’s every decision.
Clearly, people are generally unwilling to trust a fully autonomous vehicle at present. It becomes increasingly apparent that the hybrid model (Case 3) will be required to ease people from the Case 1 model into the Case 2 model. This is because the hybrid vehicle provides that backup layer of manual control that acts as a perceived security net in the event the technology should malfunction.

The significance of this extra security net is revealed when comparing responses to the third and fourth questions of interest:

- “How concerned would you be about driving or riding in a vehicle with (Level 3) self-driving technology?”, and “How concerned would you be about driving or riding in a vehicle with (Level 4) self-driving technology?”

These two questions are identical except for the level of automation – Level 3 entails limited self-driving technology where the driver is able to hand over control of safety-critical functions requiring occasional human driver input; Level 4 is completely self-driving. In essence, Level 3 still gives ultimate control to the driver (like the hybrid case) while in Level 4 the automated system holds control. From Figure 12 we observe a significant increase in ‘Very Concerned’ respondents from an average of 20% to 30% once the human loses ultimate vehicle control, with most of this increase likely coming from previously ‘Moderately’ and ‘Slightly’ concerned respondents (indicated by the fact that the number of ‘Not at all concerned’ respondents stays relatively constant between the two levels of automation, with their lack of concern likely due to full trust in autonomous technology). Note that the overall number of concerned people is ~88%, agreeing with another recent survey regarding adults being worried about riding in driverless cars (Borcherding, 2014).

This demonstrates a strong correlation between degree of human control and human willingness to adopt autonomous technology. The likely causation of this relationship being due to lack of human trust in fully autonomous technology was also illustrated in the first two questions of interest. From this it is clear that people are currently far more willing to adopt technology where they still hold ultimate control. Considering autonomous braking is only one function (i.e. doesn’t encompass controls like steering) it is more likely to be adopted by humans than a full autonomous package but there will nonetheless be initial resistance as people require time to become accustomed to driving.
with this new technology. As such, initially it would be preferable to implement a hybrid case where humans still have the ability to control the brakes in order to enable a smoother and large scale transition to a system where there is no human-brake interface (Edwards, 2014) – allowing complete autonomous brake control and eliminating human-brake errors as in Case 2.

Furthermore, at this point in time the ability of autonomous vehicle control systems to navigate non-urban environments is a very difficult challenge yet to be solved (Kelly et al., 2006), limiting the vehicle’s range. All these factors indicate that the hybrid control case (Case 3) will have a vital role to play in encouraging large-scale adoption of fully autonomous technology such as fully autonomous braking (Case 2) in order to allow for the public to develop greater trust in autonomous control while also giving researchers time to improve fully autonomous capabilities like the vehicle’s range.

Also, it appears that current trends in technology and human behaviour will necessitate a shift over to completely autonomous driving. These trends and their consequences are as follows:

<table>
<thead>
<tr>
<th>Trend</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increasing confidence in, and use of, cell phones by drivers</td>
<td>This is representative of a broader overall increase in driver distraction with the advent of mobile devices (NHTSA &amp; NOPUS, 2011). Increased driver distraction increases reaction time and subsequently reduces driver performance leading to more accidents (Fitch et al., 2013). Makes human drivers more dangerous.</td>
</tr>
<tr>
<td>Reduction in driver ability as they rely more and more heavily on autonomous control</td>
<td>This issue feeds into itself, with degrading driver ability encouraging heavier dependence on autonomy, leading to further decrease in human driving ability (Mars, 2015). An example of what is called the automation paradox, similar to erosion of airliner pilot skills due to reliance on autopilot (Mars, 2015). Makes human drivers more dangerous.</td>
</tr>
<tr>
<td>Improvements in technology</td>
<td>Improvements to relevant technology, such as LIDAR sensors that have a sweeping cycle in the order of nanoseconds will greatly enhance the computer vision that helps control the autonomous vehicle systems such as the braking control system. Makes autonomous control safer</td>
</tr>
</tbody>
</table>

Our dependence on the autonomous control system once placed in the environment of a self-driving car has already been documented with some drivers having taken up to 17 seconds to respond to requests by the machine telling the human to take over (Lienert & White, 2015). Should these trends continue in their current directions, it will become ever more necessary to adopt fully autonomous control systems in cars to maintain an acceptable level of safety.

9. Conclusion & Recommendations

Based on the above analysis of braking control systems, it can be concluded that fully autonomous braking systems offer the greatest safety performance out of the three cases considered. There were clear benefits in terms of reaction time and reducing motor accidents, as well as noticeable energy savings and potential to improve brake lifetime. There was uncertainty over the economic benefits of implementing fully autonomous braking technology, with two scenarios (the extreme upper and moderate upper sensor cost estimates) leading to significant additional costs rather than savings.
However, it is recommended that these additional costs should not inhibit implementation of fully autonomous brakes. This is because the use of economic estimates to value human life, though financially valid, do not properly account for emotional factors and the reality of a poor quality of life at a personal level. As such, the implementation of this technology should be viewed as an ethical obligation rather than a savvy economic manoeuvre, potentially signalling a permanent change in national investments in auto-safety. The one exception to implementing this type of technology would be if the resources would save/improve more lives if diverted to another problem, such as to combat an epidemic. However, considering the severe magnitude of the issue of motor accidents in terms of human life and property damage, auto-safety would be expected to be a very high priority, at least at present.

Furthermore, the hybrid brake control case was identified as playing a key role in assisting the mass transition from human-controlled to the fully autonomous case. This is due to its importance in allowing humans to develop trust in autonomous technology while giving them the feeling of security associated with wielding ultimate control over the vehicle.

Consequently, this study recommends that hybrid braking be gradually phased into motor vehicle industries until the public comes to widely accept and trust autonomous technology. At this point, it is recommended that fully autonomously braking vehicles, without a human braking interface, be phased into the market. Note that this point between hybrid and fully autonomous will likely occur before market saturation, meaning that not all drivers need to transition to hybrid before fully autonomous can begin penetrating the market. More likely, this critical point will correspond to the point when the ‘early majority’ (as defined in Robinson’s Diffusion of Innovations) begin to adopt the technology (~17th-41st percentile of the population) (Robinson, 2009).

10. Future Considerations
In terms of future work with, there are a number of aspects that will need to be considered with the rise of autonomous control in vehicles – in this case, autonomous control of the braking system.

One of the most serious issues that will become apparent in the future is the evolution of new types of accidents, including system failures (‘death by computer’) and cyberterrorism to maliciously manipulate everything from targeted vehicles to large-scale traffic flows. Not only will these necessitate innovations in safety and security, but they will also raise legal and ethical questions:

- Who is accountable if someone is involved in an accident due to system failure?
- Is it acceptable for someone to die or be injured in a situation where they had no control (e.g. system failure) if there are less accidents overall?

There will also be a need to account for system dynamics such as human behaviour. For instance, if people think fuel efficiency is better due to the autonomous technology there seems to be an effect whereby they choose to travel more, offsetting any environmental benefits. This is known as the rebound effect (Litman, 2013) and has been observed in the case of improved efficiency from lightweighting vehicles (Stasinopoulos, 2013).
Finally, it is important to note that there will always be a need to continue improving the performance and reliability of autonomous control systems in an effort to reach the point of complete elimination of accidents. The future holds potential developments like fully autonomous vehicles that could further increase safety by removing the need for any sort of human driver interface at all. Without this need for an interface, the space originally occupied by the interface could be redeveloped to maximise safety, such as removing glass windshields as humans no longer have to always look out the front window, or replacing the steering wheel and various meters with softer materials that help reduce impact forces in the event of a collision.

With this in mind, it can be seen that we have already managed to achieve great improvements with technology thus far – as in the case of autonomous braking. However, there is still room for improvement, such as eliminating all the human error-related accidents altogether – that would be a reduction of over 90%.
Appendix A – Back-of-the-Envelope Calculations:

**Estimating distance travelled in 1 additional second by car with velocity 100km/h:**

\[ \text{distance} = \text{velocity} \times \text{time}; \, \text{velocity} = \frac{100 \text{km}}{3600 \text{sec}} = \frac{100 \times 10^3 \text{m}}{3600 \text{sec}} = 27.8 \text{ms}^{-1} \]

This means that in 1 second i.e. time = 1s

\[ \text{distance travelled} = 27.8 \times 1 = 27.8 \text{m} \]


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