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The AUC Undergraduate Journal of Liberal Arts and Sciences is a biannual, interdisciplinary publication showcasing outstanding undergraduate academic papers. The Journal aims to demonstrate the strength of undergraduate scholarship at AUC, to reflect the intellectual diversity of its academic programme, to encourage best research and writing practices, to facilitate collaboration between students and faculty across the curriculum, and to provide students with opportunities to gain experience in academic reviewing, editing and publishing. The Editorial of the Journal is constituted of members of the InPrint board, a registered AUCSA committee.

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Foreword

In the semester prior to graduation, every AUC student is required to carry out an independent research project within their intended major (Sciences, Social Sciences or Humanities), referred to as the Capstone. This project is meant to have students engage with the current academic dialogue within their fields. With this year'€™s Capstone Issue, which includes six capstones across all three majors from students from the class of 2018, InPrint showcases the ability of AUC students to generate insightful interdisciplinary research.

Additionally, all Capstones published in this issue have undergone a meticulous editing process carried out by the Editorial Board of InPrint to further improve their clarity. A workshop providing the basic tools for this editing process was provided by lecturer and linguist Dr. Lotte Tavecchio. Finally, assistance with the LaTeX 2$_{\varepsilon}$ formatting for this issue was graciously provided by former Editor-in-Chief Phillip Hartout.

We hope that reading this capstone issue gives our readers both insight into the high level of academic achievement of AUC students as well as how the integration of skills and talents achieved through a liberal arts education can come together to create something truly excellent.

Lanie Preston, on behalf of InPrint

Contents

Sciences

The Impact of a Transition to Autonomous Vehicles on Total Energy Consumption in the Passenger Vehicle Transport Sector in the Netherlands

Julian Visser

Abstract

With new autonomous driving technologies being developed by many car manufacturers, an often unanswered question remains what the impact on the total energy consumption of such a transition would be. Using the Netherlands as a case study, this study researches the effects on the total energy consumption of passenger vehicles in the Netherlands, if a transition to autonomous electric vehicles (AEV) were realized. Note that this study focuses on a double transition, from fossil fuel to electric powered and man controlled vehicles to autonomous vehicles, which both affect the energy consumption differently. Results were gathered through modeling the energy efficiency effects using the available data from the Dutch passenger vehicle transport sector. It was found that total energy consumption will decrease 5.1% or even up to 57.2% in a best-case scenario. However, if only considering the effects of a transition to autonomous vehicles (thus leaving out the electrification of vehicles), energy consumption can either increase 23.2% (worst-case scenario) or decrease 28.2% (best-case scenario), showing the uncertainty of the impact of a transition to autonomous driving.

Keywords and phrases: *Autonomous Vehicles, Passenger Vehicles, Electrification, Transition, Netherlands*

Introduction

In recent years, the use of Artificial Intelligence (AI) has developed rapidly, including in the vehicle industry. Vehicle manufacturers, such as Tesla and BMW, are already implementing AI into our everyday vehicles in the form of lane assist and automated parking. Behind the scenes, companies are working hard towards putting more AI technology in our vehicles to simplify and, eventually, achieve completely autonomous driving. With new intelligent assists coming out every year, we will most likely ultimately reach autonomous vehicles (AV). Over the past decade, energy consumption of the passenger vehicle transport sector in the Netherlands has been slowly declining (CBS 2017d); however, on a global scale energy consumption of the transport sector is on the rise (Conti et al. 2016)(Herzog et al. 2005)(Bashmakov et al. 2014). With climate goals set, energy efficiency increases and energy savings have become important agenda items for political programs.

In the literature, the focus of studies on AV is often focused on their driving behaviour compared to that of vehicles controlled by humans. Instead, this paper addresses the differences in energy consumption of Autonomous Electric Vehicles (AEV) and vehicles controlled by humans.

To narrow down the scope of the research, this study compares human controlled and AEV, as if they co-existed on the same road, making use of the same infrastructure. It must be said that AV perform better with increasing numbers, as it is possible for AV to communicate with one another, thus increasing traffic fluidity considerably (Meyer et al. 2017). However, studies on these systems are limited and remain mainly theoretical, as these AV have not yet been tested on a larger scale. Furthermore, this study only considers passenger vehicles, thus excluding heavier transport, such as trucks. The study thus answers the following question: What will be the impact of a transition to electric autonomous passenger vehicles on the energy consumption in the transport sector of the Netherlands?

To answer this question a model has been developed to calculate the impact of AEV on energy consumption for different scenarios. To find the difference in energy consumption between AEV and vehicles controlled by humans, where the main focus is on driving behaviour differences between AI and humans, which is determined by the areas of vehicle movement (entailing air resistance, accelerating/braking, AI power consumption and rolling resistance) and navigating. Further implications of AEV on energy consumption, such as their influence on vehicle accidents, vehicle aesthetic developments and eventually infrastructure development differences, will also be discussed shortly.

Research context

An elaborate overview of current studies on energy efficiency increases and decreases due to autonomous driving is given by Wadud et al. (2016). In this overview studies researching energy efficiency increases due to a transition to AV were compiled. The various fields discussed are: congestion mitigation, automated eco-driving, platooning, improved crash avoidance and what they call "right-sizing" of vehicles. Regarding energy efficiency decreases due to a transition to AV, the paper mentions one possible increase: the total travel time by passenger vehicle, which is caused by both a reduction in time spent driving (i.e. making driving less of hassle) and possible new user groups of these AV (ie people that cannot currently drive but would be able to with the introduction of AV). Lastly, the paper covers potential fuel mix changes, suggesting that a transition to AV could overcome some of the hurdles of alternative fuels, thus leading to a reduction in fuel emissions intensity. However, they leave the quantitative analysis of this topic to further research.

This study differs from Wadud et al. (2016), in its focus on the Netherlands by providing a figure on both individual and national scale in either energy consumption increase or decrease of a transition to AEV. The various subsections mentioned in the introduction together with the areas of energy consumption mentioned by Wadud et al., will provide guidance material to the research. Further research on these subsections is discussed below.

An interesting model for the energy consumption of a moving vehicle is given by Mackay (2009). According to Mackay there are three energy consumers for vehicle movement. To simplify his model of the energy consumption for vehicle movement, he claims that there are two different regimes during driving, the "Accelerating and Braking" regime and the "Air Resistance" regime. During short driving distances the "Accelerating and Braking" is the dominant consumer of energy, while for longer stretches with less regular braking aerodynamic drag becomes increasingly important. Mackay calculates that for some (by him defined, see Appendix A.1) average vehicle the Accelerating and Braking regime becomes the dominant energy consumer when the braking distance is less than 750 meters, while the Air Resistance regime is the dominant regime for braking distances above this value. Besides the two regimes, Mackay identifies a third energy consumer of vehicle movement as the rolling resistance, which is always present and depends on your speed. The combination of the formulas describing energy consumption of the two regimes and rolling resistance, provide a relatively accurate model of the total energy consumption of a moving vehicle.

The formulas discussed by Mackay (2009) are used as a basis for the model in this study. These formulas will be further discussed in the methodology. However, first more research regarding the energy consumption of both AV and conventional vehicles will be discussed, as well as research covering decreases in energy consumption due to AEV.

He et al. (2012) calculated energy efficiency increases in AV in urban areas as a result of an energy management system and a cycle optimization algorithm. Using predictive traffic data, this algorithm managed to increase fuel efficiency by 56-86% for conventional vehicles. Applying this algorithm to a plug-in hybrid electric vehicle boosts fuel efficiency to roughly 115% due to the plug-in hybrid electric power management system. Translating fuel efficiency to energy consumption, we find that autonomous conventional vehicles use 35.8% to 46% less energy than their human controlled counterparts. For plug-in hybrid electric vehicles we find that this value is 53.5%. Comparing these values, it can be concluded that an AEV (in this study semi-electric) has additional benefits besides autonomous driving. Therefore, we must note that the transition to electric vehicles also has an impact on energy consumption within the transport sector. Further research on this topic has been done by Ambel (2017), which gives an extensive overview of energy efficiencies of electrical engines, internal combustion engines and fuel cells, also entailing the refinement of the fuel source. In this study it is shown that electric vehicles, powered exclusively by renewable energy, are far more efficient than the other two possibilities (similar efficiencies are concluded in Yazdanie et al. (2014)). However, the current Dutch electricity production is not exclusively based on renewable energy sources. Research on the electricity composition in the Netherlands is done yearly by Energie Onderzoek Nederland (Energy Research the Netherlands, ECN) and Centraal Bureau voor de Statistiek (Statistics Netherlands, CBS), ECN's most recent report is Schoots et. al (2017), while CBS can provide data from 2015 (CBS 2017c). Furthermore, Ambel (2017) assumes that electricity consumed for the refinement of the other fuel sources is also exclusively generated by renewable energy sources. These assumptions are important to note and are taken into account whenever figures from this research are used in the study.

Furthermore, Mensing et al. (2013) showed, through research similar to He et al. (2012), that a driving algorithm, which they call eco-driving, is able to decrease energy consumption up to 34% in urban areas. However, they argued that eco-driving does not take safety for the passenger into consideration. Therefore, the actual decrease in energy consumption in everyday use lies in the range of 15% to 28%.

As was mentioned by Wadud et al. (2016), slipstreaming (platooning) could have significant impact on fuel consumption and thus energy consumption. Duan et al. (2007) studied the effect of slipstreaming on Californian highways by using both an experimental setup and a model. During the research they varied the distance between the slipstreaming vehicles and the type of vehicles. Experimental results showed a 61% drag reduction for the second vehicle, while the model showed 40-60% drag reduction (again for second vehicle) due to platooning. Similarly, Wadud et al. (2016) discusses a decrease from 45% up to 55% for highway driving. Comparable research has been done by Zhu and Yang (2011). This study used computational fluid dynamics to simulate the flow field over two generic sedans and then compared this to the flow field of a single sedan. Based on the difference in flow fields, comparisons on the aerodynamic drag were done, resulting in a clear relation between the distance separating the two vehicles and the drag coefficient of the second vehicle. Furthermore, platooning also showed effects on the drag coefficient of the leading sedan, as its rear-end air flow was disturbed by the closely following second sedan. Nevertheless, this effect was significantly smaller than the decrease in drag coefficient for the second sedan, leading in an overall drag coefficient reduction due to platooning. This effect was around 10% if only two sedans were participating in the platoon. However, in an urban setting slightly different values were found by Zabat et al. (1995). They found that, due to platooning, on average vehicle energy consumption could be lowered 5-10% in an urban setting.

Research regarding rolling resistance of passenger vehicles has already been done by a variety of institutes and studies. In ’Fundamentals of Vehicle Dynamics’ Gillespie (1992) devotes a short chapter to rolling resistance, where he mentions that on average the rolling resistance coefficient is around 0.015 for passenger vehicles on concrete roads. Furthermore, Gillespie discusses energy consumption in the two regimes very similar to Mackay (2009), thus further supporting the model set up by Mackay. More data on rolling resistance for passenger vehicles has been collected by Société de Technologie Michelin (2003). Results from this study were comparable to values found in Gillespie (1992). Additionally, the Société de Technologie Michelin (2003) concludes that the rolling resistance stays constant up to 120 km/h.

Another possible decrease in energy consumption of AV was presented in the form eco-routing by Boriboonsomsin et al. (2012). Eco-routing is an optimization algorithm and suggests to the driver the route that uses the least fuel. The study found that eco-routing could translate into a 13% decrease in fuel consumption. However, there is a major drawback to eco-routing: choosing the optimal route fuel wise often leads to concessions on the time spent driving. Therefore, the decrease in fuel consumption comes accompanied with an increase in travel time of 5-20% (Meyer et al. 2017).

Taking a step back and looking at research focusing on direct effects of a transition to AV, we find that Meyer et al. (2017) provides a thorough research on traffic fluidity impacts of such a transition. According to this study, AV will increase accessibilities significantly as traffic fluidity increases. However, an increase in accessibility will also increase travel demand (Hills 1996), counteracting decreases in total energy consumption. Nevertheless, the positive impact of traffic fluidity overrules the negative effects of higher travel demands. An additional positive effect of a transition to AV on traffic fluidity not mentioned by Meyer et al., is the decrease in vehicle accidents. According to NHTSA (2008) up to 90% of the accidents in the United States are caused by human errors. Research done by Bertoncello and Wee (2015) showed that after a complete transition to AV up to 190 billion dollars could be saved for the United States economy alone.

Scope and limitations

The scope of the study is to quantify the impact of a transition to AEV on the energy consumption in the passenger vehicle transport sector in the Netherlands. As has become clear in chapter 2, such a transition has two elements that influence energy consumption: the transition to autonomous driving and the transition to electric vehicles from conventional vehicles. Therefore, the research question should be split into two parts: the transition to autonomous vehicles and the transition to electric. After separating, the effects of these transitions are calculated for a single vehicle. Finally, the separated effects are combined, and the impact on a national scale is calculated. Both of these questions require a variety of other questions to be answered first.

- What is the average difference in energy consumption between a single autonomous passenger vehicle and a single conventional passenger vehicle in the Netherlands?
  - What is the effect of platooning on the drag coefficient of AV?
  - How does autonomous driving influence energy consumption during accelerating and braking?
  - What is the average speed of vehicles in urban and non-urban areas?
  - What is the average braking distance of vehicles in urban and non-urban areas?
  - What is the average energy consumption of an average vehicle?
  - What is the power consumption of AI driving a vehicle?
- What is the average difference in energy consumption between a single electric passenger vehicle and a single conventional passenger vehicle in the Netherlands?
  - What is the average motor efficiency of EV and conventional vehicles in the Netherlands?
  - What is fuel production efficiency for petrol?
  - What is the electricity mix in the Netherlands?

A number of limitations exist concerning this study. Although CBS can provide a wide variety of data, speed averages in urban areas and non-urban areas are unknown. Similarly, braking distances for these two areas are also unknown. Therefore, this study takes averages based on the earlier explained ground rules. If these values differ significantly from real values, results from this study become unsuitable for the Netherlands.

Furthermore, this study will not take any increases or decreases in vehicle use due to AV (Meyer et. al 2017) into consideration. Additionally, it will also not acknowledge any other benefits from autonomous driving, nor will it recognize any pros or cons of human-driving. For example, it is theorized that due to wireless interaction among AV, traffic fluidity can become even further increased than what has been suggested in this paper. Traffic lights, roundabouts, intersections and speed bumps could become obsolete. However, some participants (cyclists, pedestrians, etc.) are not able to communicate with these AV, so this raises new problems regarding infrastructure. Most predictions therefore remain speculative and hard to quantify. Thus, in the trend of not acknowledging any other benefits of a transition to AV, energy consumption influences from infrastructure changes will not be considered. In other words, this study focuses solely on the energy consumption of conventional vehicles and AEV in the Netherlands. Any societal changes (and their accompanied energy consumption in/decreases) from a transition to AEV are left for other studies to analyze. Nevertheless, it should be noted that even if a transition to AEV causes major societal changes in passenger vehicle use, results from this study regarding individual energy consumption of AEV are still be applicable.

Relevance

The transportation sector makes up 29% of total world energy consumption (EIA 2018) (see pie chart below), of which roughly 50% can be ascribed to passenger vehicles (Conti et al. 2016). So, global energy consumption consists of a significant part of passenger vehicles, meaning that any energy efficiency increases could have major effects. Additionally, environmental scientists have suggested energy efficiency increases in a variety of sectors, preferably major energy consuming sectors, to meet the goals stated in the 2015 Paris climate agreement (Bashmakov et al. 2014)(Pachauri et al. 2014). Considering the hefty energy consumption of passenger vehicles in the transportation sector, the sector applies well for potential energy efficiency increases. Therefore, this study looks into the effect on energy consumption of a transition to AEV. From this study one could either find reason to stimulate AEV or continue research into different areas of energy efficiency increases in the transportation sector. Therefore, this study provides the figures to help make the right decisions towards meeting the 2015 Paris climate agreement in the Netherlands. Furthermore, this study could lay the foundation for various other studies in other countries concerning their transition to AEV, as this study will thoroughly describe the aforementioned model and will consider a wide range of possible scenarios dependent on the level of urbanization, average vehicle speeds and average braking distance. Although results from this study may not be directly applicable to other countries, the results will nevertheless provide a good indicator of the effectiveness on energy consumption of a transition to AEV.

Methodology

Literature review

As was clarified in chapter 2, the energy consumption of a passenger vehicle depends on a wide variety of components. Data concerning the energy consumption of both AEV and human controlled vehicles will be needed to eventually make an accurate calculation. Details on traffic in the Netherlands is mostly be provided by CBS, which is deemed to be a highly reliable source. Any other claims concerning differences in energy efficiency between AEV and human controlled vehicles are supported by the available literature. Most literature was acquired through CataloguePlus (the database of the University of Amsterdam). A summation of some the keywords for finding current research in this field were: *Autonomous, Self-driving, Efficiency, Cars, Vehicles, Platooning, Eco-driving, Eco-routing, Electric, Plug-in Hybrid, Transition, Artificial Intelligence and Rolling resistance*. Lastly, snowballing techniques were used to efficiently get more in-depth papers for specific details and values.

The Model

To answer the research question a model is created, based on a model for vehicle movement set up by Mackay (2009) and adjusted for AEV whenever needed. The figure below shows the basic steps that are required to calculate the energy consumption of AEV in the various regimes for a specific braking distance. Below the figure the formulas needed for the calculations are explained, starting with the separate parts that have to do with the energy consumption of a car, which are used to calculate the average speeds in urban and non-urban areas.

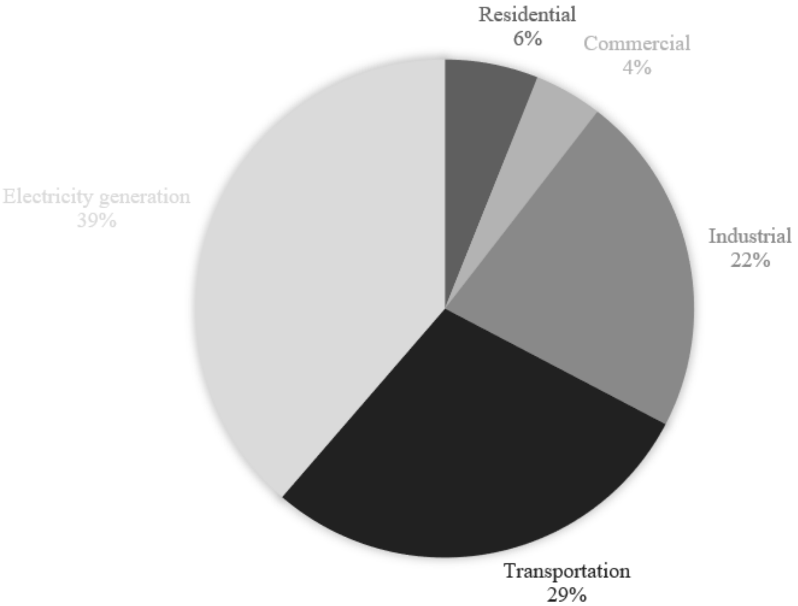
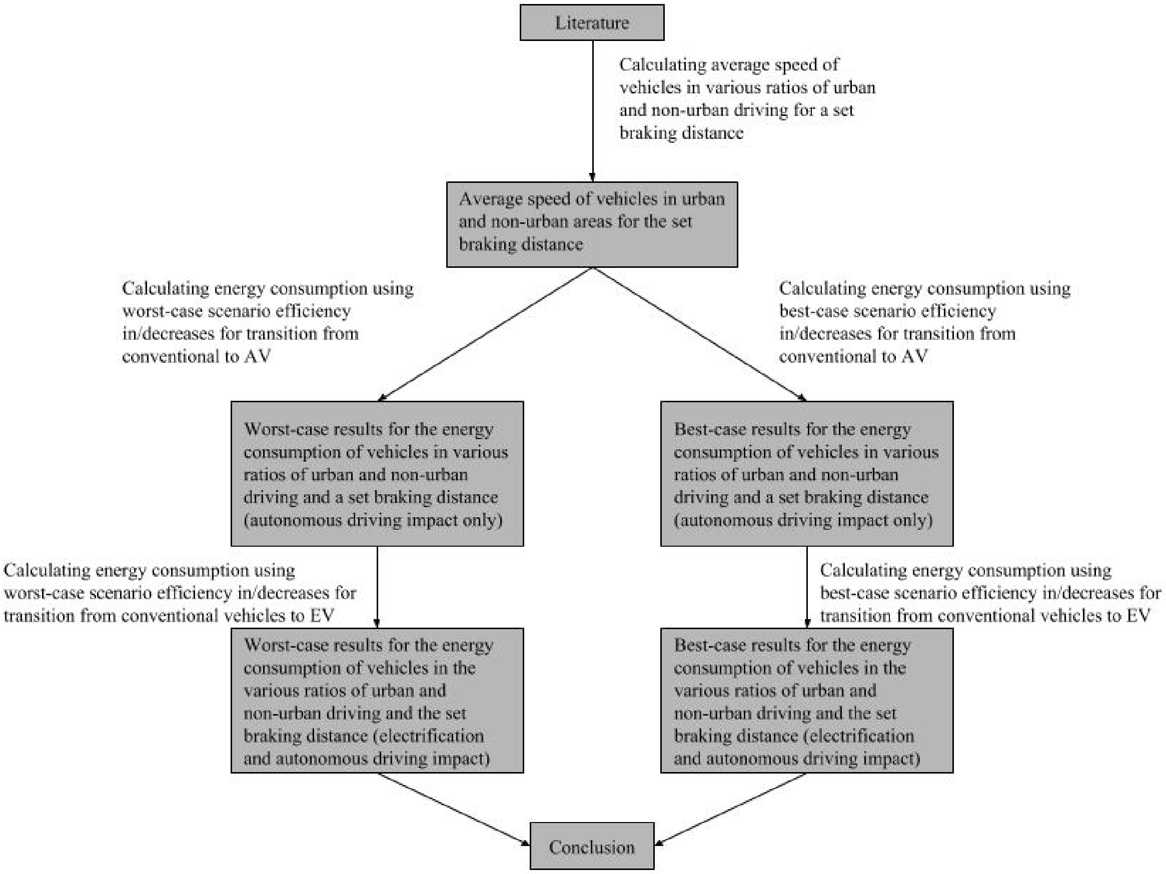


Figure 1: Primary energy consumption by sector (Based on EIA (2018))



Steps to calculating energy consumption for AEV for a specific braking distance

Accelerating and Braking regime

Imagine a driver driving in a city, where he constantly needs to accelerate and brake due to traffic lights. Every time the driver is halted by a traffic light he hits the brakes and converses all his kinetic energy into heat in his brakes. Depending on the distance between the traffic lights and his or her speed, he or she has to hit his brakes after every x amount of seconds. Therefore, the driver consumes energy at the following rate:

$$\text{Power}_{accelerating\ and\ braking} = \frac{E_k}{\text{time between braking events}} = \frac{\frac{1}{2}m_c v^2}{\frac{d}{v}} = \frac{m_c v^3}{2d}, \quad (1)$$

where E_k is the kinetic energy of the vehicle, m_c is the mass of the vehicle, d the distance between braking events and v the speed of the vehicle. However, this formula does not take regenerative braking into consideration, which is a standard in EV. The efficiency of regenerative braking is about fifty percent, and thus halves the energy lost during braking:

$$\text{Power}_{accelerating\ and\ braking\ AEV} = \frac{m_c v^3}{4d}. \quad (2)$$

Air Resistance regime

While driving through the city, the vehicle also consumes energy by plowing through the air. As the vehicle moves, it is essentially moving air from one place to another, thus giving the air kinetic energy. The kinetic energy of moving air can be described by:

$$\text{Kinetic energy of moving air} = \frac{m_{air} v^2}{2} \quad (3)$$

m_{air} can be rewritten by imagining that the vehicle creates a vehicle shaped tube in the air it has driven through. This tube of air can be described by $\rho c_d A_{vehicle} vt$ (the density of the air, drag coefficient of the vehicle, area of the vehicle, speed of the vehicle and time driven respectively). To then energy consumption of air resistance we simply divide by the time, finding

$$\text{Power}_{air\ resitance} = \frac{m_{air}v^2}{2} = \frac{\rho c_d A_{vehicle} vtv^2}{2} = \frac{\rho c_d A_{vehicle} v^3}{2}. \quad (4)$$

Rolling Resistance

Mackay discusses rolling resistance as the final energy consumer of vehicle movement. Calculations with the rolling resistance combine all rolling inefficiencies of a car in to C_{rr}. With this value the energy consumption is calculated to be:

$$\text{Power}_{rolling\ resitance} = C_{rr} m_c g v. \quad (5)$$

Total Power Consumption of Vehicle Movement

Combining formulas (2), (4) and (5), the total energy consumed to move a human controlled vehicle is given by

$$\text{Power}_{total} = \frac{\rho c_d A_{vehicle} v^3}{2} + \frac{m_c v^3}{2d} + C_{rr} m_c g v. \quad (6)$$

Note that this formula needs to be adjusted for the efficiency of the motor. Furthermore, this formula also needs to be modified to be applicable to AEV, as the A.I. driving the vehicle must be taken into consideration. So for an AEV we find:

$$\text{Power}_{total\ AEV} = \frac{\rho c_d A_{vehicle} v^3}{2} + \frac{m_c v^3}{4d} + C_{rr} m_c g v + \text{A.I. power consumption} \quad (7)$$

The increase in energy consumption due to the AI power consumption of driving an AEV is significant. Current autonomous prototype vehicles approximately consume 2000 Watts, compared to human drivers, who use roughly 20 Watts, this number is enormous (Welling 2017)[1].

Setting up the Model Scenarios

Many areas where AEV have a higher energy efficiency than conventional vehicles were discussed in chapter 2. Most of these efficiency increases apply to one of the driving regimes or a specific area of driving, where the difference seems to lie between urban and non-urban driving. Average driving speed differs enormously in these two areas, which influences energy consumption in the specific driving areas. Therefore, the model separates energy consumption in urban and non-urban areas by accounting for two different average speeds. Adjusting formula (6) accordingly, it transforms into:

$$\text{Power} = \frac{\rho c_d A_{vehicle} v^3_{non-urban}}{2} + \frac{\rho c_d A_{vehicle} v^3_{urban}}{2} + \frac{m_c v^3_{urban}}{2d}$$
$$\frac{m_c v^3_{non-urban}}{2d} + C_{rr} m_c g (v_{urban} + v_{non-urban}). \quad (8)$$

Similarly adjusting formula (7) leads to

$$\text{Power AEV} = \frac{\rho c_d A_{vehicle} v^3_{non-urban}}{2} + \frac{\rho c_d A_{vehicle} v^3_{urban}}{2} + m_c v$$
$$\frac{m_c v^3_{non-urban}}{4d} + C_{rr} m_c g (v_{non-urban} + v_{urban}) + \text{A.I. power consu}$$

To calculate energy consumption of *one* passenger vehicle using (8), the braking distance and average speed (in both urban and non-urban areas) are needed. However, these variables are unknown for the Netherlands. Luckily, CBS has done research on travel time, travel distance, vehicle weight, total energy consumed by all passenger vehicles, and the total amount of passenger vehicles (CPS 2016c)(CBS 2017d)(CBS2017a)(CBS2016a), making it possible to calculate average power consumption for a conventional vehicle (Appendix A.2). From here, a solution for the *speed* in urban and non-urban areas can be calculated through (9) using two variables: the *distance* covered in urban and non-urban areas and the *braking distance* in urban and non-urban areas (all other variables are retrievable through sources or are calculated in Appendix A). Both these variables are unknown for the Netherlands, therefore the model calculates average speeds for 5 different ratios of distance covered in and outside urban areas. The ratios are 1:1, 5:1, 1:5, 3:2, 2:3, based on an average travel distance of about 32 kilometers (Appendix A.4). So for the ratio 5:1, 26.7 kilometers were driven in ur-

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[1] Although this figure comes from a respectable Dutch newspaper, the actual source is from a less respected magazine named Wired. This source does not provide the origin of the figure

ban areas, while 5.3 kilometers were traveled in non-urban areas. Furthermore, each ratio is analyzed for a set of braking distances, consisting of 100, 200, 300, 359, 400, 500 and 700 meters. The braking distances are chosen based on rounded average distances found between crossings, roundabouts and traffic lights in Amsterdam. The values stop at 700 meters, as for higher values for braking distance, energy losses due to braking become negligible. The urban vs non-urban ratios are determined based on a variety of travel routes in the Netherlands. Combining the ratios and braking distances with the average power consumption per vehicle (See appendix B for the various calculations), formula (8) provides a range of combinations of time spent in and outside urban areas, and thus average speed in these areas. To determine the right combination of time spent in urban and non-urban areas, the total travel time must be considered. The two times found with formula (8) must add up to a total travel time of 2484.6 seconds (see appendix A.5), limiting the range of results.

Applying Efficiency Changes to the Model

After artificially generating average speeds for urban and non-urban areas in the Netherlands, formula (9) is used to calculate the energy consumption of AEV. This is where the energy efficiencies discussed in the research context are applied. Depending on the area of impact of the efficiency increase, the model is altered. Additionally the mass of the car is altered, as electric vehicles are slightly heavier than their Internal Combustion (IC) counterparts (See Appendix B). First, a worst-case scenario is considered, where only the lowest energy efficiency increases are applied and no eco-routing is considered. Thereafter, a best-case scenario is calculated where the model is altered using the best energy efficiency increases and eco-routing. A list of energy efficiency changes for both scenarios is given below (values are based on researches discussed in the research context). Note that for the calculations of the efficiency of the electric and IC engine energy losses due to the mining of the raw material (e.g. coal, gas etc.) were neglected. Energy lost during these processes are minimal, moreover as they occur in both scenarios (electric and IC) these effects roughly cancel, making it acceptable to leave the effects out.

These efficiencies will impact the energy consumption of an AEV. Therefore, formula (9) is adjusted to entail all efficiency changes. In the worst-case scenario this produces:

$$\text{Power} = \frac{1}{0.319}\Big(0.9\frac{\rho c_d A_{vehicle} v^3_{non-urban}}{2} + 0.85 * 0.95\frac{\rho c_d A_{ve}}{}$$

$$0.85 * 0.95\frac{m_c v^3_{urban}}{4d} + \frac{m_c v^3_{non-urban}}{4d} + C_{rr} m_c g(v_{non-urban} + 0.85$$

Likewise, in the best-case scenario we change formula (9) to:

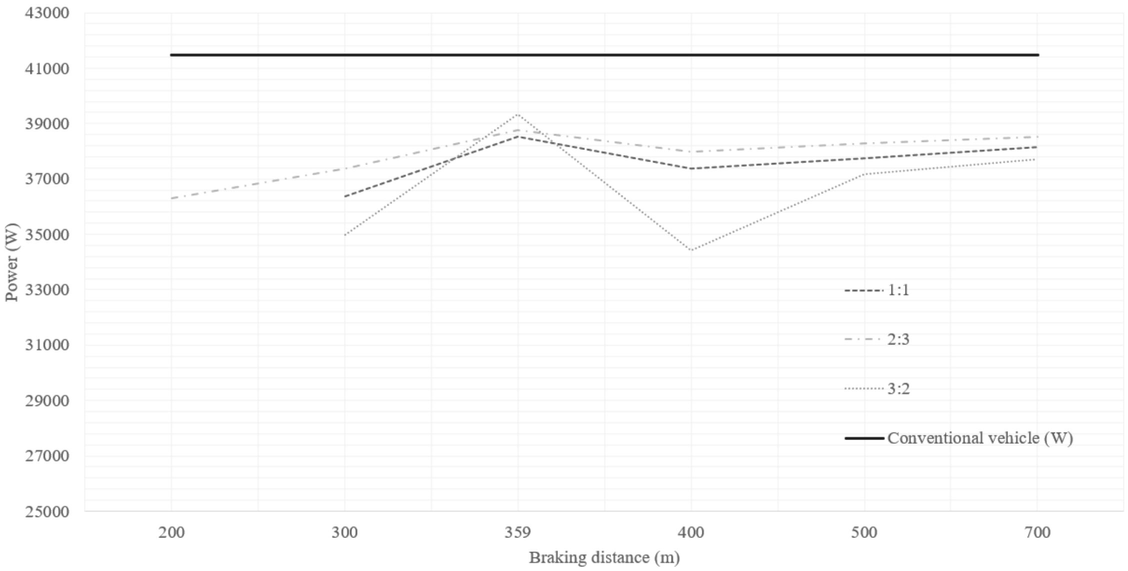
$$\text{Power} = \frac{1}{0.428} * 0.87\Big(0.45\frac{\rho c_d A_{vehicle} v^3_{non-urban}}{2} + 0.54 * 0.9$$

$$0.54 * 0.9\frac{m_c v^3_{urban}}{4d} + \frac{m_c v^3_{non-urban}}{4d} + C_{rr} m_c g(v_{non-urban} + 0.54 *$$

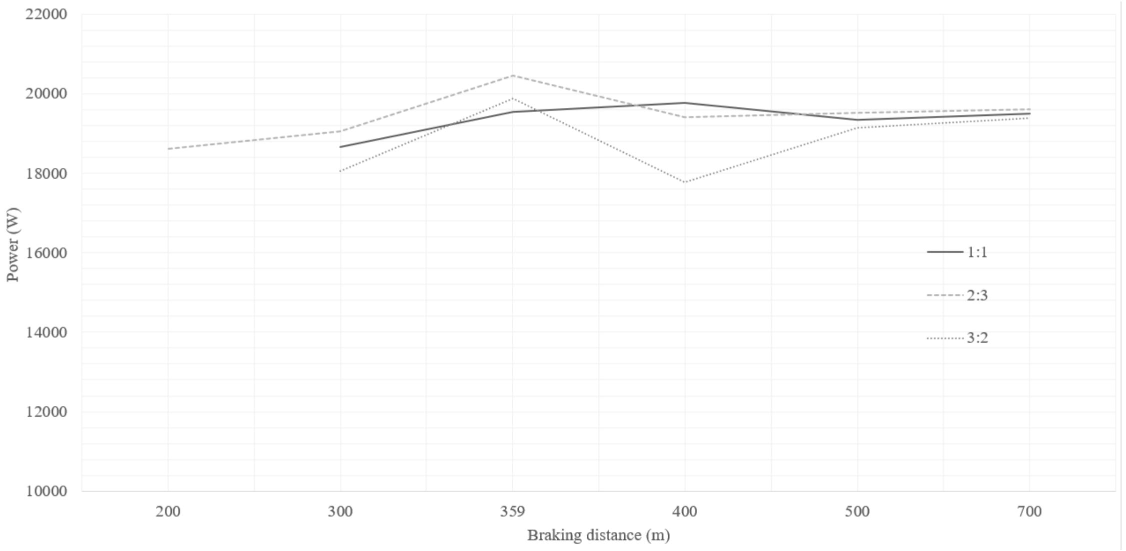
Using the average speeds artificially determined through formula (8), which is done in Appendix B & C, the power consumption of AEV can be calculated in a worst (using 10) and best (using 11) case scenario for various braking distances.

Results

With the varying braking distance and ratio of urban an non-urban driving, a range of average speeds was found. Non-realistic average speeds (i.e. speeds far below speed limits in the Netherlands) were filtered from the results, leaving a limited amount of possible braking distances and ratios that could apply to the Netherlands. The ratios 5:1 and 1:5 are therefore excluded from the results entirely. The following graph shows the energy consumption of conventional and AEV for various braking distances and ratios of urban and non-urban driving, if the worst-case scenario is applied.



Worst-case Scenario AEV Energy Consumption Compared to Conventional Vehicle Energy Consumption



Best-case scenario AEV energy consumption (note that conventional vehicle energy consumption has been left from the graph, as it roughly 20000 Watts higher).

Even in the worst-case scenario, AEV consume slightly less energy than their conventional counterparts. On the other hand, with the best-case scenario energy consumption of AEV drops far below conventional vehicles energy consumption.

However, this shows the energy consumption impact of both the transition to electric *and* autonomous vehicles. If we are to solely look at the impact of a transition to autonomous driving a different result was observed, as now in the worst-case scenario energy consumption of autonomous vehicles is higher than for that of a conventional vehicle.

Concluding from the figures, a transition to AEV can in both a worst and a best-case scenario only mean a decrease in total energy consumption. In the very worst-case we find a decrease of 5.1%, while a best-case scenario could mean a decrease in energy consumption up to 57.2%. However, results from the calculations are quite different when the same fuel source is considered. By considering the same fuel source, energy consumption decreases from a transition to electricity as fuel are neglected and thus only the (dis)advantages from autonomous driving become apparent. Looking at the worst-case scenario an increase in energy consumption of 23.2% can be found. Nevertheless, in a best-case scenario, we still find a decrease in energy consumption of 28.2%. Using the results, it can be concluded that just the shift from oil-based fuels to electricity alone provides a decrease in energy consumption of 9.1% and 25.5% in the worst and best-case scenario, respectively. Furthermore, it can be noticed that (especially in the best-case scenarios) energy consumption slightly increases with braking distance, apart from some anomalies that will be discusses below. This increasing energy consumption can be explained by the increasing average speeds in non-urban areas. With increased braking distance, less energy is lost in urban areas; nevertheless, the way the model is oriented, the total energy consumption must remain the same when calculating average speeds. The model then compensates for this decrease in energy consumption by increasing average speed in non-urban areas. Next, when efficiency changes are applied, something interesting happens. Efficiency impacts in urban areas are higher than in non-urban areas: 70% versus 10%, and 119% versus 68%. Therefore, if less energy is consumed in non-urban areas (as breaking distance increases) less energy can be saved and thus the total energy consumption increases. Albeit that in the worst-case scenario this trend cannot be seen clearly in the 3:2 ratio, the other scenarios do follow expectations more evidently, but more on this ratio later.

Additionally, we can observe that in the worst-case scenario, energy consumption in the 1:1 ratio of urban and non-urban driving is consistently lower than energy consumption in the 2:3 ratio. Apart from the anomaly at the 359 meter braking distance, the 3:2 ratio shows similar traits with regards to the 1:1 ratio. This can be explained through the importance of regenerative braking, as in urban driving, more energy can be saved through this method, while in a worst-case scenario, only limited energy savings were deemed possible. In the best-case scenario, we see that the various ratios are more strongly intertwined. This is due to other increases in energy efficiency that were only considered in the best-case scenario, such as platooning, eco-routing, and eco-driving. This allows for a relatively smaller gap between urban and non-urban efficiency changes. Evidently, these energy efficiency increases (mostly more effective on the highway) can overpower the impact of regenerative breaking. Although, percentage-wise, the efficiency increases in urban areas are higher (119% versus 68%), on average far more energy is consumed on the highway (speed influences energy consumption to the third power) thus allowing this gap to level, as is seen in the best-case scenario.

Lastly, it is remarkable that the energy consumption, if only looked at a transition to AV, is higher for the AV compared to the conventional vehicles (in a worst-case scenario). This can be explained through the energy consumption of the AI controlling the car. Although this AI causes improved driving efficiency (even in a worst-case scenario) it uses around 2000 Watts to accomplish this. Considering that a conventional vehicle only uses 10574 Watts (100% car efficiency), the AI power consumption has a serious impact on the total energy consumption.

Although a conclusion can be drawn from the results, some anomalies do exist. Throughout the results for all ratios in all graphs, a peak in energy consumption can be noted at a braking distance of 359 meters. This peak can be described through the average urban and non-urban speeds associated with it. Looking at the data, we see a recurring theme where (compared to speeds at all other braking distances) urban speed decreases disproportionately while non-urban speeds increase significantly. This causes energy consumption to rise significantly because of the discrepancy between energy efficiency in urban and non-urban areas, as has been discussed earlier. To this list of anomalies the decrease in energy consumption in the ratio 3:2 between the braking distance 300 and 400 meters can be added. Once again, we see the interesting interaction between the energy efficiency differences in urban and non-urban areas. In this case, the average speeds do follow expectations, however, average urban speed decreases more significantly between these two points. This allows for a decrease in energy consumption despite an increase in braking distance.

Conclusion

This paper introduced a model to evaluate the energy consumption of AEV compared to conventional vehicles. A variety of energy efficiency increases in AEV were considered, including eco-routing, platooning and eco-driving. Additionally, the impact on energy consumption due to a transition to electric vehicles was both considered together with and without the autonomous part.

Undergoing a transition to AEV (so both the transition to electric and autonomous vehicles) an 5.1% to 57.2% decrease in energy consumption can be observed for the worst- and best-case respectively. However, a large part of this decrease in energy consumption is due to the electrification of the vehicles. If only the impact of autonomous driving on energy consumption is considered (+23.2% to -28.2%), there exists a serious uncertainty whether the transition is beneficial in terms of the total energy consumption. Both ranges of the impact on energy consumption are wide, therefore further research is needed, helping to map the energy efficiencies of a transition to autonomous driving better. Furthermore, to conclude on a specific figure for the Netherlands further research on braking distances and ratio of urban and non-urban driving is required, as the observed energy consumption differs up to 11.1%, when all energy efficiency changes are kept constant and the scenario is altered.

Discussion

This study has only covered well-known (and documented) areas of car movement where a transition to AEV decreases or increases energy consumption. However, there are many uncertain effects that could have a significant impact on energy efficiency. Firstly, as has been discussed in the research context, a complete transition to autonomous vehicles could decrease the number of accidents by 90%, saving up to 190 billion dollar (Bertoncello and Wee 2015). Although not directly connected to the movement of a car, energy consumption costs regarding damage done to surroundings and vehicles could be seen as part of the total energy consumption of the sector. Therefore, although complicated, the number of accidents that are prevented due to AV could theoretically be transcribed into energy savings. Furthermore, a significant decrease in accidents due to AV could make safety measurements in vehicles potentially obsolete. Therefore, it has been suggested that in the future, current safety measures might be removed, decreasing vehicle weight and thus increasing movement efficiency (Meyer et al. 2017). Additionally, electric vehicle weight might decrease due to the further developments in the battery industry. Currently, batteries contribute significantly batteries to the weight of electric vehicles, but with increased use and intensive research batteries might become more powerful, and thus lighter in the future.

Most of these energy savings remain unknown, and could present themselves to be negligible; nevertheless, further research into these topics is needed to conclude their significance. However, some imminant changes in the electricity mix have a far more certain impact on the energy consumption of AEV. Future plans for electricity production in the Netherlands promise a strong increase in renewable energy sources (Schoots et al. 2017). Currently, renewable energy supplies 13.8% of Dutch electricity (CBS 2017e), and the European Union aims to achieve 20% renewable electricty by 2020. Thus, in the short term, renewable energy sources will grow, further advocating for a transition to electric vehicles and possibly AEV. Additionally, we may expect increases in the energy efficiency of the AI driving the car, as the autonomous vehicle market is still developing. In the past, we have seen that AI software updates could increase driving range, suggesting increases in efficiency of the AI.

However, not all future changes have a positive impact on the energy consumption of AEV. As autonomous vehicles do not require any attention or driving skills, various sources suggest possible increases in vehicle use (Meyer et al. 2017)(Wadud et al. 2016). An increase in use of passenger vehicles will bring along an increase in the total energy consumption of the passenger vehicles transport sector, which could potentially diminish any energy saved due to the transition to AEV.

Although one would expect average speed in urban areas to go up as braking distance increases (less braking incidents meaning less slowing down, thus keeping a higher average speed), some of the results, as has been discussed, show different behaviour. Therefore, although the model suggests that energy consumption drops when braking distance is at 400 meters, it could be a flaw in the model. Similarly the peak experienced throughout the ratios at a braking distance of 359 meters might be due to a flaw in the model. A potential problem could be that the model only considers two areas of driving combined with two different braking distances, while in reality, many more areas of driving exist. Therefore, it is suggested that future models differentiate more areas of driving while simultaneously acknowledging the various braking distances in these areas. However, this was beyond the possibilities of this study due to a lack of data. Nevertheless, this study believes that creating a more extensive model will smooth out the aforementioned inconsistencies.

Taking the variety of uncertainties (and unknowns) in energy efficiency impacts of autonomous driving into consideration, the effect of a transition to AEV is still difficult to quantify. This can clearly be seen in the results of this study, as their range is extremely wide. Therefore, further research on these energy efficiency changes is desperately needed, as car manufacturers have predicted that production of fully autonomous cars could start within five years. To find a more accurate number for the Netherlands, further research on braking distance in urban and non-urban areas as well as an accurate ratio for urban and non-urban driving will be needed. Luckily, CBS is currently looking into this topic, and will be able to provide figures by the start of 2019.

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A Model Values Calculations

A.1 An Average Car According to Mackay

The values used by Mackay to calculate energy consumption of an average car are given here:

Table 2: Vehicle Model Calculation Parameters (Mackay)

Parameter	Value
Air density	1.3 kg/m^3
Vehicle Area	3 m^2
Mass of car (conventional)	1000 kg
Rolling resistance	0.010
Gravitation of earth	9.81 m/s^2
Drag coefficient car	0.33

A.2 Average Power Consumption Dutch passenger vehicles

The following facts, provided by CBS, make it possible to calculate the average power consumption of a single passenger vehicle in the Netherlands.

Data type	Amount
Number of Dutch passenger vehicles (CBS 2016a)	8100864
Total Dutch passenger vehicles energy consumption (CBS 2017d)	259 PJ
Average car travel time per person per day (CBS 2016c)	19.76 minutes
Number of inhabitants of the Netherlands (**?**)CBS 2017b)	169790120
Average efficiency of conventional car engine (Ambel 2017)	30 %

First it is necessary to calculate average travel time per car per year. This is done through:

$$\text{Yearly travel time per person} * \frac{\text{\# of inhabitants}}{\text{\# of passenger vehicles}} = \\ 60 * 365 * 19.76 * \frac{169790120}{8100864} = 906879 \text{ Seconds per car.} \quad (12)$$

Then we simply divide total energy consumption by this number and keeping car engine efficiency in mind:

$$\frac{259 * 10^{15}}{906879 * 8100864} = 35249 \text{ Watts per car} \Rightarrow 35249 * 0.3 = 10574.8 \text{ Watts per car for car movement.} \quad (13)$$

Do note that this energy consumption is only from tank to wheel. Total energy consumption should be determined through the Well-to-Wheel (WTW) analysis. Especially during the refining of oil energy losses occur. These losses are well known and average around 15% (Pachauri et al. 2014). Therefore, total energy consumption for car movement is 41469 Watts ($35249 * \frac{1}{0.85}$).

A.3 Average Weight Dutch Passenger Vehicles

CBS also gathers information on the amount of passenger vehicles that fit in a certain weight class (CPBS 2017a). The data is slightly more recent than used in A.1, however car weight is not strongly volatile, so this causes no problem.

$$\frac{\text{Total Weight Dutch Passenger Vehicles}}{\text{Amount of Dutch passenger vehicles}} = \frac{9748327375}{8373244} = 1164.22 \text{ kg} \quad (14)$$

A.4 Average distance covered per car per day

CBS also has data on the average travel distance by passenger vehicle per person (CBS 2016c). To translate this to the average travel distance per car we write, similarly to 12,

$$\text{Average travel distance per person} * \frac{\text{\# of inhabitants}}{\text{\# of passenger vehicles}} = 15.14 * \frac{169790120}{8100864} = 31.73 \text{ km.} \quad (15)$$

A.5 Average Travel Time per Day per Car

Simply using the total yearly travel time per car found in A.1 we find

$$\frac{\text{Yearly travel time per car}}{\text{\# of days in the year}} = \frac{906879}{365} = 2484.6 \text{ s.} \quad (16)$$

A.6 Efficiency of Electric Vehicle Engine

To calculate the efficiency of an electric engine we need to consider production efficiency of Dutch electricity as well as the energy efficiency of the engine itself. Ambel states that the average electric engine efficiency lies at 90%. However, energy losses (5%) due to inversions from AC to DC and vice versa and battery charging inefficiencies (5%) have to be considered. Furthermore, data on the Dutch electricity can be found through CBS (CBS 2016b), while average power plant efficiencies were determined in Paling (2013). The results of these inefficiencies are combined in the following table.

Table 3: Electricity Production Efficiency

	% of total electicity production	Average power plant efficiency (%)	
Natural Gas	0.42	45-60	
Coal	0.36	30-45	
Fuel oil	0.00087	30-45	
Other fossil fuels	0.036	30-45	Worst-case efficiency
Solar	0.010	100	31.9 %
Wind	0.069	100	
Hydro	0.00085	100	
Biomass	0.045	20-40	
Nuclear	0.037	30-35	Best-case efficiency
Other energy carriers	0.026	30-45	42.8%

B Calculations with the Vehicle Model

In this section all calculations with the vehicle model can be found. The values found from the calculations were used to set up graphs in Wolfram Mathematica, which were in turn used to determine average speeds for urban and non-urban areas. The model formula has been rewritten as

$$\text{Power} = A_1 v_{non-urban}^3 + A_1 v_{urban}^3 + B_1 v_{urban}^3 + B_2 v_{non-urban}^3 + C_1(v_{urban} + v_{non-urban}), \tag{17}$$

where A_1, $B_{1/2}$ and C_1 are calculated using values given in the table below (in combination with a varying urban braking distance and ratio urban/non-urban driving), which have already been backed scientifically in the research context, methodology and appendices. Additionally when calculating energy consumption of AEV the formula is adjusted for the increased weight. The altered value is given below and is based on the increase in weight of vehicles on the market that have both an electric and IC version.

Using these values in combination with formula (17), which is rewritten to:

$$\text{Power} = (A_1 + B_1)(\frac{x_{urban}}{t_{urban}})^3 + C_1(\frac{x_{urban}}{t_{urban}}) + \\ C_1(\frac{x_{non-urban}}{t_{non-urban}}) + (A_1 + B_2)(\frac{x_{non-urban}}{t_{non-urban}})^3 +, \tag{18}$$

We can find a range of solutions of the average time spent in both urban and non-urban areas. These solutions are found by solving the following equations, which obey specific parameters described in the table.

Table 4: Vehicle Model Calculation Parameters

Parameter	Value
Braking distance	100 to 700 m
Air density	1.2466 kg/m^3
Vehicle Area	3 m^2
Mass of car (conventional)	1164 kg
Mass of car (electric)	1414 kg
Rolling resistance	0.012
Gravitation of earth	9.81 m/s^2
Drag coefficient car	0.33
Braking distance non-urban areas(m)	Non-urban driving distance
Distance covered per car per day	31.73 km
Average power consumption of a Dutch passenger vehicle	10574

C Calculating the average speeds

Solving the formulas described in Appendix B with the boundary condition that $t_{urban} + t_{non-urban}$ is equal to 2484.6 seconds the following results were found (remember that the ratios are connected to specific values, thus to get the average speed one simply has to divide this distance by the time).

D Tables for the various scenarios

In this appendix the tables on which the graphs in the results are based can be found. Additionally these tables were used to calculate the maximum de- and increase of energy consumption.

Table 5: Urban braking distance 100 meter

Urban	26444.0802
Non-urban	5288.816041
Solve	$6.437(\frac{26444.0802}{x})^3 + 137.02(\frac{26444.0802}{x}) + 137.02(\frac{5288.81}{y}) + 0.727110533(\frac{5288.816}{y})^3 = 10574$
Urban	5288.816041
Non-urban	26444.0802
Solve	$6.437(\frac{5288.816041}{x})^3 + 137.02(\frac{5288.816041}{x}) + 137.02(\frac{26444.0802}{y}) + 0.639075707(\frac{26444.0802}{y})^3 = 10574$
Urban	15866.44812
Non-urban	15866.44812
Solve	$6.437(\frac{15866.44812}{x})^3 + 137.02(\frac{15866.44812}{x}) + 137.02(\frac{15866.44812}{y}) + 0.653748178(\frac{15866.44812}{y})^3 = 10574$
Urban	12693.1585
Non-urban	19039.73775
Solve	$6.437(\frac{12693.1585}{x})^3 + 137.02(\frac{12693.1585}{x}) + 137.02(\frac{19039.73775}{y}) + 0.647634648(\frac{19039.73775}{y})^3 = 10574$
Urban	19039.73775
Non-urban	12693.1585
Solve	$6.437(\frac{19039.73775}{x})^3 + 137.02(\frac{19039.73775}{x}) + 137.02(\frac{12693.1585}{y}) + 0.662918472(\frac{12693.1585}{y})^3 = 10574$

Table 6: Urban braking distance 200 meter

Urban	26444.0802
Non-urban	5288.816041
Solve	$3.527(\frac{26444.0802}{x})^3 + 137.02(\frac{26444.0802}{x}) + 137.02(\frac{5288.81}{y}) + 0.727110533(\frac{5288.816}{y})^3 = 10574$
Urban	5288.816041
Non-urban	26444.0802
Solve	$3.527(\frac{5288.816041}{x})^3 + 137.02(\frac{5288.816041}{x}) + 137.02(\frac{26444.0802}{y}) + 0.639075707(\frac{26444.0802}{y})^3 = 10574$
Urban	15866.44812
Non-urban	15866.44812
Solve	$3.527(\frac{15866.44812}{x})^3 + 137.02(\frac{15866.44812}{x}) + 137.02(\frac{15866.44812}{y}) + 0.653748178(\frac{15866.44812}{y})^3 = 10574$
Urban	12693.1585
Non-urban	19039.73775
Solve	$3.527(\frac{12693.1585}{x})^3 + 137.02(\frac{12693.1585}{x}) + 137.02(\frac{19039.73775}{y}) + 0.647634648(\frac{19039.73775}{y})^3 = 10574$
Urban	19039.73775
Non-urban	12693.1585
Solve	$3.527(\frac{19039.73775}{x})^3 + 137.02(\frac{19039.73775}{x}) + 137.02(\frac{12693.1585}{y}) + 0.662918472(\frac{12693.1585}{y})^3 = 10574$

Table 7: Urban braking distance 359 meter

Urban	26444.0802
Non-urban	5288.816041
Solve	$2.238(\frac{26444.0802}{x})^3 + 137.02(\frac{26444.0802}{x}) + 137.02(\frac{5288.81}{y}) + 0.727110533(\frac{5288.816}{y})^3 = 10574$
Urban	5288.816041
Non-urban	26444.0802
Solve	$2.238(\frac{5288.816041}{x})^3 + 137.02(\frac{5288.816041}{x}) + 137.02(\frac{26444.0802}{y}) + 0.639075707(\frac{26444.0802}{y})^3 = 10574$
Urban	15866.44812
Non-urban	15866.44812
Solve	$2.238(\frac{15866.44812}{x})^3 + 137.02(\frac{15866.44812}{x}) + 137.02(\frac{15866.44812}{y}) + 0.653748178(\frac{15866.44812}{y})^3 = 10574$
Urban	12693.1585
Non-urban	19039.73775
Solve	$2.238(\frac{12693.1585}{x})^3 + 137.02(\frac{12693.1585}{x}) + 137.02(\frac{19039.73775}{y}) + 0.647634648(\frac{19039.73775}{y})^3 = 10574$
Urban	19039.73775
Non-urban	12693.1585
Solve	$2.238(\frac{19039.73775}{x})^3 + 137.02(\frac{19039.73775}{x}) + 137.02(\frac{12693.1585}{y}) + 0.662918472(\frac{12693.1585}{y})^3 = 10574$

Table 8: Urban braking distance 400 meter

Urban	26444.0802
Non-urban	5288.816041
Solve	$2.072(\frac{26444.0802}{x})^3 + 137.02(\frac{26444.0802}{x}) + 137.02(\frac{5288.81}{y}) + 0.727110533(\frac{5288.816}{y})^3 = 10574$
Urban	5288.816041
Non-urban	26444.0802
Solve	$2.072(\frac{5288.816041}{x})^3 + 137.02(\frac{5288.816041}{x}) + 137.02(\frac{26444.0802}{y}) + 0.639075707(\frac{26444.0802}{y})^3 = 10574$
Urban	15866.44812
Non-urban	15866.44812
Solve	$2.072(\frac{15866.44812}{x})^3 + 137.02(\frac{15866.44812}{x}) + 137.02(\frac{15866.44812}{y}) + 0.653748178(\frac{15866.44812}{y})^3 = 10574$
Urban	12693.1585
Non-urban	19039.73775
Solve	$2.072(\frac{12693.1585}{x})^3 + 137.02(\frac{12693.1585}{x}) + 137.02(\frac{19039.73775}{y}) + 0.647634648(\frac{19039.73775}{y})^3 = 10574$
Urban	19039.73775
Non-urban	12693.1585
Solve	$2.072(\frac{19039.73775}{x})^3 + 137.02(\frac{19039.73775}{x}) + 137.02(\frac{12693.1585}{y}) + 0.662918472(\frac{12693.1585}{y})^3 = 10574$

Table 9: Urban braking distance 500 meter

Urban	26444.0802
Non-urban	5288.816041
Solve	$1.781(\frac{26444.0802}{x})^3 + 137.02(\frac{26444.0802}{x}) + 137.02(\frac{5288.81}{y}) + 0.727110533(\frac{5288.816}{y})^3 = 10574$
Urban	5288.816041
Non-urban	26444.0802
Solve	$1.781(\frac{5288.816041}{x})^3 + 137.02(\frac{5288.816041}{x}) + 137.02(\frac{26444.0802}{y}) + 0.639075707(\frac{26444.0802}{y})^3 = 10574$
Urban	15866.44812
Non-urban	15866.44812
Solve	$1.781(\frac{15866.44812}{x})^3 + 137.02(\frac{15866.44812}{x}) + 137.02(\frac{15866.44812}{y}) + 0.653748178(\frac{15866.44812}{y})^3 = 10574$
Urban	12693.1585
Non-urban	19039.73775
Solve	$1.781(\frac{12693.1585}{x})^3 + 137.02(\frac{12693.1585}{x}) + 137.02(\frac{19039.73775}{y}) + 0.647634648(\frac{19039.73775}{y})^3 = 10574$
Urban	19039.73775
Non-urban	12693.1585
Solve	$1.781(\frac{19039.73775}{x})^3 + 137.02(\frac{19039.73775}{x}) + 137.02(\frac{12693.1585}{y}) + 0.662918472(\frac{12693.1585}{y})^3 = 10574$

Table 10: Urban braking distance 700 meter

Urban	26444.0802
Non-urban	5288.816041
Solve	$1.448(\frac{26444.0802}{x})^3 + 137.02(\frac{26444.0802}{x}) + 137.02(\frac{5288.81}{y}) + 0.727110533(\frac{5288.816}{y})^3 = 10574$
Urban	5288.816041
Non-urban	26444.0802
Solve	$1.448(\frac{5288.816041}{x})^3 + 137.02(\frac{5288.816041}{x}) + 137.02(\frac{26444.0802}{y}) + 0.639075707(\frac{26444.0802}{y})^3 = 10574$
Urban	15866.44812
Non-urban	15866.44812
Solve	$1.448(\frac{15866.44812}{x})^3 + 137.02(\frac{15866.44812}{x}) + 137.02(\frac{15866.44812}{y}) + 0.653748178(\frac{15866.44812}{y})^3 = 10574$
Urban	12693.1585
Non-urban	19039.73775
Solve	$1.448(\frac{12693.1585}{x})^3 + 137.02(\frac{12693.1585}{x}) + 137.02(\frac{19039.73775}{y}) + 0.647634648(\frac{19039.73775}{y})^3 = 10574$
Urban	19039.73775
Non-urban	12693.1585
Solve	$1.448(\frac{19039.73775}{x})^3 + 137.02(\frac{19039.73775}{x}) + 137.02(\frac{12693.1585}{y}) + 0.662918472(\frac{12693.1585}{y})^3 = 10574$

Table 11: Urban braking distance 100 meters

100 meter		N. S. = No Solution			
Ratio	**Urban (s)**	**Non-urban (s)**	**Total**	**Urban (km/h)**	**Non-urban (km/h)**
5:01	N. S.	N. S.	0	N. S.	N. S.
1:05	1271	1213	2484	15.0	78.5
1:01	N. S.	N. S.	0	N. S.	N. S.
2:03	N. S.	N. S.	0	N. S.	N. S.
3:02	N. S.	N. S.	0	N. S.	N. S.

Table 12: Urban braking distance 200 meters

200 meter		N. S. = No Solution			
Ratio	**Urban (s)**	**Non-urban (s)**	**Total**	**Urban (km/h)**	**Non-urban (km/h)**
5:01	N. S.	N. S.	0	N. S.	N. S.
1:05	1287	1202	2489	14.8	79.2
1:01	1524	965	2489	37.5	59.2
2:03	1496	991	2487	30.5	69.2
3:02	N. S.	N. S.	0	N. S.	N. S.

Table 13: Urban braking distance 300 meters

300 meter					
Ratio	**Urban (s)**	**Non-urban (s)**	**Total**	**Urban (km/h)**	**Non-urban (km/h)**
5:01	2103	383.7	2486.7	45.3	49.6
1:05	1284	1200	2484	14.8	79.3
1:01	1642	842	2484	34.8	67.8
2:03	1536	948	2484	29.7	72.3
3:02	1745	739	2484	39.3	61.8

Table 14: Urban braking distance 359 meters

359 meter					
Ratio	**Urban (s)**	**Non-urban (s)**	**Total**	**Urban (km/h)**	**Non-urban (km/h)**
5:01	2141	344	2485	44.5	55.3
1:05	1266	1209	2475	15.0	78.7
1:01	1691	793	2484	33.8	72.0
3:02	1839	645	2484	37.3	70.8
2:03	1600	884	2484	28.6	77.5

Table 15: Urban braking distance 400 meters

400 meter					
Ratio	**Urban (s)**	**Non-urban (s)**	**Total**	**Urban (km/h)**	**Non-urban (km/h)**
5:01	2142	341	2483	44.4	55.8
1:05	1288	1197	2485	14.8	79.5
1:01	1669	815	2484	34.2	70.1
2:03	1551	933	2484	29.5	73.5
3:02	1794	690	2484	38.2	66.2

Table 16: Urban braking distance 500 meters

500 meter **Ratio**	**Urban (s)**	**Non-urban (s)**	**Total**	**Urban (km/h)**	**Non-urban (km/h)**
5:01	2119	329.9	2448.9	44.9	57.7
1:05	1287	1201	2488	14.8	79.3
1:01	1683	801	2484	33.9	71.3
2:03	1561	923	2484	29.3	74.3
3:02	1813	671	2484	37.8	68.1

Table 17: Urban braking distance 700 meters

700 meter **Ratio**	**Urban (s)**	**Non-urban (s)**	**Total**	**Urban (km/h)**	**Non-urban (km/h)**
5:01	2154	305	2459	44.2	62.4
1:05	1216	1258	2474	15.7	75.7
1:01	1697	787	2484	33.7	72.6
2:03	1570	914	2484	29.1	75.0
3:02	1831	653	2484	37.4	70.0

Table 18: AEV and conventional energy consumption after efficiency changes (worst-case scenario)

	1:1 (W)	2:3 (W)	3:2 (W)	Conventional vehicle (W)
200 (m)		36316		41496
300 (m)	36388	37372	34997	41469
359 (m)	38514	38772	39333	41469
400 (m)	37368	37985	34417	41469
500 (m)	37746	38285	37164	41469
700 (m)	38149	38525	35801	41469

Table 19: AEV energy consumption after efficiency changes (best-case scenario)

	1:1 (W)	2:3 (W)	3:2 (W)
200 (m)		18619	
300 (m)	18658	19055	18060
359 (m)	19533	20446	19887
400 (m)	19769	19411	17768
500 (m)	19351	19526	19151
700 (m)	19506	19616	18486

Table 20: Sole impact of autonomous driving on energy consumption rate

		Worst-case = w-c		Best-case = b-c		
	1:1 w-c (W)	2:3 w-c (W)	3:2 w-c (W)	1:1 b-c (W)	2:3 b-c (W)	3:2 b-c (W)
200 (m)		11585			7404	
300 (m)	11608	11921	11164	7839	8006	7588
359 (m)	12286	13031	12547	8207	8590	8355
400 (m)	11920	12117	11567	8306	8156	7824
500 (m)	12041	12213	11856	8130	8204	8047
700 (m)	12169	12289	12033	8196	8242	8140