# Methodology for assessing the potential of using automated vehicles as an access/egress mode for train trips in a regional setting

An application to the province of Utrecht





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October 1<sup>st</sup>, 2015 Thesis-MSc. Transport, Infrastructure and Logistics, Delft University of Technology

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# PREFACE

This research focuses on developing a methodology for assessing the potential of using automated vehicles as an access/egress mode for train trips in a regional setting and is my final step out from TUDelft as a MSc. student in Transport, Infrastructure and Logistics.

Firstly, I would like to thank my professors from TUDelft, namely Bart van Arem, Goncalo Correia and Jan Anne Annema for their help, cooperation and advises during the entire project. Special thank you I would like to dedicate to my company's supervisor Menno Yap, a wise person that helped me not only in terms of advises and project input, but most importantly for opening my scope and push myself a step further every time. A special thank you I would like to say to my former professor from NTUA, professor Dimitris Milakis, whom I met in TUDelft and helped me not only find a research topic for my thesis, but also advised me several times, when I needed help.

Moreover, I would like to thank all my colleagues of Goudappel Coffeng that helped me during my research, and especially Niels van Oort for his pitched comments, as well as Rogier Koopal and Arnout Kwant, who both helped me countless times in modelling issues. I will always remember all and think of them with gratitude.

Furthermore, I could not neglect thanking my friends from Greece Elena, Panagiota, Litsa, Chrissy, Ioanna and Marina, as well as my friends in the Netherlands Dolores, Nadezda, Jorge, Natasa and Dimitris, who all supported, advised, listened and comforted me every time I was feeling stressed, lost or disappointed. And of course, all the people I met during the past two years for the special moments they offered me. I will always remember them.

Special thank you to my parents and my sister that were by me through the entire studies in the Netherlands and supported me, although they were far away. I could not make it without them.

Finally, I would like to thank my boyfriend, Haris, who was an angel through all these 2 years I was studying. He was amazingly supportive, comforting, he advised me several times and I could not thank him enough for all that.

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The automated vehicles are considered as the upcoming future of transportation. Many researches have addressed already on the technical characteristics and aspects of the automated vehicles, as well as the methodologies to incorporate them to the current transport network in terms of infrastructure, land use distribution, capacity and route adaptations. However, still important issues remain unsolved, such as the passenger safety on the automated vehicles, legal issues and the expected reliability of the communication systems that support the operation of the automated vehicles. The points that this research is elaborating, which the current literature has not investigated yet, are two:

- Investigation of potential demand for automated vehicles as access/egress mode for train trips: No researches have been so far generated for the public transport network, regarding the investigation of potential demand for automated vehicles as access/egress mode for train trips, and especially for low/medium demand train stations and their impacts in public and private transport demand in general.
- Introduction of a systematic Cost-Benefit Analysis (CBA) as an evaluation tool for the implementation of the new mode: So far, the available literature regarding the costs and benefits of the operation of the automated vehicles is focusing only on the financial aspects of this new operation, without taking into account broader perspectives such as the passengers and the society.

Taking into consideration these two points, the research focus of this project is crystallised in the following research question:

# What methodology can be developed for the systematic scanning and evaluation of areas in order to identify potential for fully automated vehicles as egress/access modes for low/medium demand train stations?

This methodology is investigating the potential of introducing the automated vehicles into a regional setting, by identifying the highest potential train station-zones-routes combinations and evaluating these combinations in terms of demand and costs-benefits.



Aspects examined in the project for implementing automated vehicles as access/egress mode choice for train trips

So, based on the research question stated above, a methodology is developed, as illustrated below. The methodology is a stepwise approach, structured in 3 main parts: identification/design process, determination of cases and evaluation process.

#### Methodology-PART A: Identification/Design Process

PART A of the methodology is consisted of three levels: train station, zone and route level. In the first two levels, an identification process is involved for finding the highest potential train station and its associated zones, in order to implement the automated vehicles as an access/egress mode for train trips. The third level is a design process for the potential routes that the automated vehicles would operate on. Zooming in to each level:

- For the train station level, the objective is to find the highest potential train station, based on 3 identification criteria: 1) daily train trips per train station, 2) access/egress mode demand per train station and 3) maximum potential zones associated. The last criterion is a zone-oriented criterion, which is satisfied via 5 constraints, applied to each associated zone. These constraints are: 1) mode/purpose demand per zone, 2) association of zones only to one train station, 3) location of zones from train station further than walking/cycling distance, 4) daily bus service level per zone and 5) maximum number of potential zones per train station. The application of the 3 criteria is an exclusion process, filtering out the train stations and choosing, eventually, the highest potential train station.
- For the zone level, the objective is to find the highest potential zones, associated to the train station chosen in the previous level, according to 5 identification criteria: 1) daily trip volumes, 2) total bicycle share, 3) bicycle share for work/business purposes,
  4) bicycle share, compared to car and PT share, and 5) bicycle share for work/business purposes, compared to car and PT share, for the same purposes.

These criteria are applied simultaneously, for which zones are evaluated and ranked. The ranking of the zones is used as input information for PART B of the methodology.

- For the route level, the objective is to choose the highest potential routes that connect the chosen train station and associated zones. The design is accomplished via 5 criteria, applied simultaneously: 1) capture of maximum demand, 2) attractive travel distances, 3) congestion levels, 4) operational speed and 5) allowance of motorised modes. The potential routes derived are further used as input for PART B of the methodology.
- In the zone level, a *sensitivity analysis* is performed, as well as a *validation*, associated to both train station and zone level.

#### **Methodology-PART B: Determination of Cases**

In PART B, different cases are determined, namely potential combinations of train stationzones-routes that the automated vehicles would serve. The choice of the highest potential train station is established in the train station level of PART A. The choice of zones and routes, however, is dependent on: 1) the number of zones chosen, 2) special network aspects and 3) operational characteristics of existing network. So, based on these dependences for the choice of zones and routes, in this part, different train station-zonesroutes cases are created, which are further evaluated in PART C.

#### **Methodology-PART C: Evaluation Process**

PART C of the methodology is evaluating the cases derived from PART B, based on two sets of criteria: 1) demand-related criteria and 2) cost-benefit analysis criteria. The first set involves 4 different demand aspects that are examined per case (AV users, train users, access/egress mode users from/to the chosen train station and modal split of each chosen zone). The second set incorporates systematic criteria for six main effect areas (investment, fares, travel times, operational and maintenance costs, externalities and levy), all associated to different stakeholders/perspectives of the system affected (e.g. passengers and society). The outcomes per case are translated into monetary values for each criterion in a CBA framework, used as an evaluation tool for the potential cases. The purpose of this part is to define the effects of implementing the automated vehicles, in terms of demand and costsbenefits, for each case.



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The methodology developed is further applied to the province of Utrecht in the Netherlands, the main outcomes of which are summarised below.

#### **Application of Methodology-PART A: Identification/Design Process**

PART A is applied into the case study, which generated the following outcomes:

- The application of the train station identification level revealed Veenendaal Centrum as the highest potential train station for implementing the automated vehicles. Regarding the zone identification level, the ranking process designated 4 highest potential zones, while in relation to the route design level, two route scenarios are pre-determined: current bus line route scenario and shortest path route scenario. Based on these scenarios, one route per scenario is determined in the network.
- The sensitivity analysis and the validation justified the choices of Veenendaal Centrum and the 4 highest potential zones.

#### **Application of Methodology-PART B: Determination of Cases**

PART B is applied with fixed the 4 zones and the two route scenarios pre-defined in PART A, for decreasing the number of possible options. So, only two cases are evaluated in PART C:

- Case 1 Current Bus Line Based: In this case, the automated vehicles are implemented as access/egress mode for Veenendaal Centrum and the 4 zones chosen, by operating on a route that is following the bus lines (with the respective bus stops) that currently serve the chosen train station and zones.
- Case 2 Shortest Path Based: This case is using the automated vehicles as access/egress mode choice for Veenendaal Centrum and the 4 selected zones in a route that would serve them with the shortest travel distance in total.

#### **Application of Methodology-PART C: Evaluation Process**

PART C is applied to each of the two cases. The starting point is the first set of evaluation criteria, namely demand-related criteria, with the main outcomes summarised below:



The number of total AV users per day is approximately 600 passengers for case 1 and 500 passengers for case 2. Moreover, the daily AV users boarding/alighting in the stop outside the train station of Veenendaal Centrum are approximately 300 passengers for case 1 and 200 for case 2. Possible explanation for both outcomes is the higher

Methodology for assessing the potential of using automated vehicles as an access/egress mode for train trips in a regional setting-An application to the province of Utrecht connectivity offered in case 1, compared to case 2.

> The number of daily train users in Veenendaal has Centrum increased approximately bv 20 passengers for case 1 and decreased by 40 for case 2. These outcomes could be explained by the fact that case 1 is offering higher connectivity than case 2, outweighing the shorter travel distance (and time) advantage of case 2.



Train user changes for case 1 and 2 in train station Veenendaal Centrum

- The access/egress mode users outside the train station of Veenendaal Centrum switched to automated vehicles with higher volumes in the first case (approximately 30 daily access/egress passengers for automated vehicles), rather than in the second (approximately 10 daily access/egress passengers for automated vehicles). Again, the connectivity advantage offered in case 1 could explain the difference in AV access/egress users.
- In respect to the modal split changes for each of the 4 zones served by the automated vehicles, public transport demand increased (in which the automated vehicles are included). The positive changes of PT for each O-D matrix per zone are between 0,18-0,45% for the first case and between 0,22-0,55% for the second.

The second set of evaluation criteria are reflecting broader perspectives affected by the implementation of the automated vehicles into the existing system and are incorporated into a systematic CBA. The execution of the CBA on both cases revealed the following:

- Both cases have a positive Net Present Value (NPV). The NPV of the first case is close to the break-even value (+ 3 €millions), while the NPV of the second case is considerably high (+ 45 €millions).
- The benefits after the implementation of the automated vehicles into the existing network for both cases derive from two main effect areas. Firstly, from the positive car externality effects (+ 19 €millions for case 1 and + 26 €millions for case 2). And secondly, from the positive in-vehicle travel time effects on the BTM users (+ 7 €millions for case 1 and + 13 €millions for case 2).
- ➤ The main costs in both cases are coming from the O&M costs that automated vehicles require (-12 €millions for case 1 and -11 €millions for case 2).
- The difference of the NPV between the first and second case derives a) from the higher benefits coming from car externalities and in-vehicles travel time effects for BTM users for case 2, compared to case 1 and b) from the positive effects on waiting

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travel times for BTM users in case 2 (+20 €millions), compared to the negative effects on waiting times of BTM users for case 1 (-8 €millions).

In total, the evaluation has revealed that, although case 1 is scoring slightly better in terms of pure demand-related criteria, case 2 is scoring far more positive in the CBA.

#### **Conclusions and Recommendations**

Summarizing the research in general, the methodology developed is focusing on finding the highest potential train station-zones-routes combination/case in terms of demand and costbenefit ratio. This methodology is applied to the province of Utrecht and provided a lot of outcomes regarding the choice of the highest potential train station-zones-routes cases, as well as the outcomes of the evaluation of each case for potential demand and costs-benefits of the new mode. The conclusion is that the automated vehicles could attract demand, not only for the new system, but also for the train station chosen and the PT modes of the area in general. Moreover, the CBA showed that the automated vehicles could also be viable in terms of cost-benefit ratio.

However, further investigation is required, regarding the methodology itself, as well as the application of the methodology. Special attention is requested on the choices and further adjustments of the modelling parameters used (Value of Time, disutility functions, vehicle specifications etc.) and adoption of more criteria for further insight on automated vehicles (e.g. special people groups, emission rates per area, spatial changes). Finally, this methodology could be used as a tool for future researchers/modellers/policy makers to investigate the potential of introducing automated vehicles into the existing network, taking also into account the potential of replacing existing low demand bus lines by automated vehicles.

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## **1 INTRODUCTION**

#### **1.1 Insight on Automated Transport Systems**

Transportation is a necessity, a desire, an endless action of human that is inevitably connected to the modes, infrastructure and urban structure available. The transition of years has resulted in all kinds of differences such as the framework of transportation (technologies used, infrastructure built etc.), the demand and the distance travelled, but not the travelling itself. Increase of demand has led to an incremental need for new transport solutions in order to cover the demand, which is followed by longer travel distances and generating again new demand. This cycle of actions is evolving throughout the years and will continue to exist, with the main centre of this cycle being the non-stop efforts in finding solutions in transportation, in order to satisfy the demand and reach the potential distance expectations.

On one hand, transportation is offering various opportunities to people (commute, socialize, vacation etc.). On the other hand, it is accompanied with various side effects. Ioannou, (1997) has summarized the main problems associated with transportation to be congestion, new, projected growth and mobility issues. These problems can be degraded through expansion or modification of the transport system. Baskar, et al. (2008), in their research, point out the traffic congestion problems and their negative effects on mobility, environment and connectivity. Based on their opinion, in order to solve this problem, a possible solution would be, to some extent, the building of new roads. But, this decision is restrictive due to lack of space, financial costs and environmental constraints. For this reason, maybe the solution relies on the usage of the existing infrastructure and the efficient incorporation of traffic management and traffic control.

However, as implied above, although the efforts for resolution of the transport problems are continuous, some of them are difficult to be solved. According to Wee, et al. (2013), the main reasons for these transport problems are the economic growth and increase of population, which led to the expansion of the households further away, with an autonomous way (individual initiative). Moreover, they mention that many measures, regarding the transportation field, have not being tuned in sufficiently with each other, resulting in non-effective transportation networks, both operationally and economically.

The past few years, a great attention has been spotted on the environmental side of transportation and its general effects. The footprint that the environment is leaving behind is enormous. According to the European Commission (2011), the transport sector accounts for the 30% of the total energy consumption, whereas the  $CO_2$  emission rates reach more or

less the same percentages. The breakdown of total emissions for the transportation in 2008 is 71.3% for road, 15.3% for maritime, 12.8% for aviation, and 0.7% for rail transport, revealing the thoroughly negative contribution of the road transport to the total environmental pollution levels. In Figure 1.1, the percentile contribution on final energy consumption and  $CO_2$  emissions for major sectors are depicted, with transportation and industry featuring in both aspects with a summed percentage of over 50%. On the same wavelength, Wieczorek & Hekkert (2010) mention that most economies are highly dependent on fossil fuels, resulting in large depletions of resources, loss of biodiversity and general pollution of the environment, a situation that requires innovative policies and technological changes.



Figure 1.1: Left: Energy consumption per sector. Right: CO<sub>2</sub> emissions per sector (Source: PRIMES and projections based on TRANSTOOLS for maritime. Retrieved from Commission, (2011))

#### 1.1.1 Automated vehicles: a breakthrough or a break down?

Taking into consideration the facts and opinions stated above, the answer to transport related problems may be the automation in transportation, and more specifically the automated vehicles (both in private and public transport). A lot of people, however, are wondering *why* to use automated vehicles. The answer is simple: *why not?* As David Strickland, administrator of the National Highway Traffic Safety Administration (NHTSA) in the U.S. said in his speech at the Telematics Update conference in Detroit, June 2011 (NHTSA, 2013): "*A car is a car*". In a similar way of thinking, automated vehicles are nothing more than another transport mode. However, the novel and differentiating features of this mode, compared to the regular modes, is the level of human monitoring, control and intervention during driving, as well as the energy used and consumed. In fact, Ioannou (1997) provided insight to the human perspective of the automated vehicles, namely the human inability to cope with constant reflexes during driving and the precedence that the automated vehicles have in terms of speed of reaction.

Yigitcanlar, et al. (2008) highlighted five crucial points that are connected to sustainable transport and consequently to automated vehicles: the finite quantity of petroleum, the atmospheric pollution, the congestion, the accidents and fatalities, and finally, the currently inherent spread of transport systems that occupy land and are connected to excessive transport/land (and not only) costs. Moreover, Meyer (2014) is elaborating on the positive impacts of automated vehicles on traffic efficiency, environmental emissions, road safety and elimination of accidents caused by human factors. Similar opinions regarding the positive contribution of the automated vehicles to numerous of impact areas are proposed by SMART (2011), iMobility (2013) and Varotto, et al. (2014). However, even though the automated vehicles could provide numerous of benefits to the problems identified above, still the costs associated to this mode are existing and unavoidable. The infrastructure adjustments required, the purchase of the automated vehicles, the control systems required and many more costs, are connected to the new mode system, and thus, request careful consideration (Kerr, et al., 2005). Further elaboration on the benefits and costs of the automated vehicles is presented in Appendix A.1.

#### **1.1.2** Definition of the automated transport systems

The introduction of automation in transportation is reflected in researches for both public ((Yigitcanlar, et al., 2008), (May, et al., 2012)) and private transportation ((Hoogendoorn, et al., 2013), (Kocks, et al., 2014)). The researches, regarding automation in public transportation, refer to the network level, namely to public transport networks that could include or could be replaced by automated vehicles (this replacement is closely related to the level of automation chosen for each public transport mode) and the respective adjustments in vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communications. On the other hand, automation in private transportation (private cars) is determined on the private driver level (mostly) and the respective technologies to achieve it, using as centroid the car. In general, either on a network or private driver level, automated vehicles have in both cases a common characteristic: the level of automation regarding the human's driving and intervention.

Interest and research for the automated vehicles has been arisen in the past few decades, beginning from the 70's until today ((USCommitte, 1975), (Ioannou, 1997), (Berns & Puttkamer, 2009), (SMART, 2011)). Most of the researchers define automation in transport as related to the levels of automation, as proposed by NHTSA and SAE ((NHTSA, 2013), (SAE, 2014)), considering mainly five levels of automation, from manual driving to full automation, a fact that is also supported by other researchers as well ((Gasser & Westhoff, 2012), (Hoogendoorn, et al., 2013), (iMobility, May 2013), (Varotto, et al., 2014)). For more information regarding the detailed description of the levels of automation, as described by NHTSA and SAE, see Appendix A.2. Finally, some researchers even make a step further in this definition by incorporating, besides the levels of automation, the involvement of the cooperative systems (V2V and V2I) into the definition (Meyer, 2014). Detailed description of the current technological support of cooperative systems to the automated transport systems are presented in Appendix A.3.

#### 1.1.3 First researches and case studies of automated vehicles

The history of the automated vehicles is starting from the late 1930's even, and more specifically, from General Motors at the 1939 World's Fair. There, General Motors presented for the first time their vision regarding the automated vehicles and their contribution as transport mode in the existing transport network. After this first implication, the first concrete framework for Automated People Movers and Personal Rapid Transit systems started to develop in 1953, whereas in 1955, the first concept for Automated Guided Vehicles, created for material transport purposes in industrial settings, is introduced by Thompson & Brooks (2010). Moreover, Ioannou (1997), who focused on automation in both vehicle and infrastructure decision making tasks by introducing the concept of automated highway systems, presented the first appearances of activities and demonstrations related to these systems in the 1950's in USA and in the 1960's in Europe and Japan. In the Netherlands, the first pilot programs that have been introduced in the past are the ones in Schiphol airport and in Floriade (2getthere, 2015).

The first case studies and pilot programs of automated vehicles appeared and were applied in the 70's (Raney & Young, 2005), with a lot of upcoming researches and applications ((Sadayuki, et al., 2001), (Thompson & Brooks, 2010), (Bouraoui, et al., 2011), (2getthere, 2015), (CityMobil2, 2015)). However, almost all of them had or have a short time horizon of operation, besides some exceptions, such as the Morgantown People Mover that is still operating.

CityMobil and 2getthere have made a lot of efforts on the field of automated vehicles in the last years, but they are not the only ones. CityMobil2 is continuing these efforts with present and future pilot programs on cybernetic mobility in 8 towns and cities in Europe, such as Milan, La Rochelle and Trikala (CityMobil2, 2015). The Dutch Automated Vehicle Initiative (DAVI) is elaborating on the *investigation, improvement, valuation and demonstration of automated driving on public roads* (a cooperation between TUDelft, Connekt, RDW, TNO, Toyota Motors Europe and many other Dutch and selected international partners) (Hoogendoorn, et al., 2013). In addition, in the research of SMART (2011), there are a lot of other projects regarding automated vehicles in general.

Furthermore, some of the most important projects of PRT (People Rapid Transit) and GRT (Guided Rapid Transit) (further explanation of the PRT, GRT and other categories of automated vehicles is provided in Appendix A.4), currently running, are the ones in Morgantown, the Rivium ParkShuttle in Rotterdam, the automated transport systems in Masdar, Suncheon and in Heathrow airport (2getthere, 2015). Future hosting cities for automated vehicles will be also Hsinchu and Amritsar (2getthere, 2015). A final comment is that each project above defined different operational characteristics of the vehicles, depending on the needs of each project. These vehicle characteristics determine the maximum speed, the capacity and the dimensions of the vehicles, the vehicle-to-vehicle headways and every operational aspect of the vehicle and in association to its surrounded environment (see Appendix A.5 for more details).

#### 1.1.4 Issues for further investigation

Automated vehicles, although they have a lot of benefits, this does not eliminate the fact that it is an innovation currently developed. This means that, in order to be operational, current technology and knowledge requires further evolvement. In the research of SMART (2011), the importance of obtaining high reliability levels for the ADAS-based automated driving and of the V2V and V2I based cooperative driving is pointed out, a request underlined by both manufacturers and legislators. Also, since the automated vehicles and the human driven modes both use the same networks, their interaction and coordination is very important to be guaranteed. Another important perspective is the human behaviour in automated driving under certain traffic situations that will cause authority transition from the automated driving system to the human. This is further researched by Varotto, et al. (2014), who highlight the current knowledge gaps upon this issue.

The resolution of certain problems and the establishment of additional benefits by the automated vehicles is not necessarily the panacea of everything, nor will prevent the generation of "side effects". Gasser & Westhoff (2012) presented the theoretical potential of vehicle automation for traffic safety (Figure 1.2) and clearly automated vehicles can contribute to the elimination of major parts of the transport safety problems, though not entirely, whereas they pointed out the creation of new problems that were not existent before (accidents due to (new) risk of automation).



Figure 1.2: Accident prevention and newly generated accident risks from automated vehicles (Source: Report of the BASt Expert Group. Retrieved from Gasser & Westhoff, (2012))

Besides the technology and knowledge that is available towards automated vehicles, other problems currently not solved, such as the integration of these vehicles to the legislator system of transportation, is a topic that requires special attention. The legal aspect of this new mode is something unclear regarding the boundaries and rules around this topic. However, the regulation is not only reflected in a strategic level, but more importantly on an operational and tactical one, implying the need for small and large scale adjustments. Gasser & Westhoff (2012) concluded from their research that there is an inherent request for *"taking the driver out of the loop"*, when talking about automated driving. Upon this regulatory consistency path, the California Department of Motor Vehicles (DMV) has also driven, which is assigned from September 2012, to define the regulatory framework for the testing and operation of automated vehicles on California's public roads (Soriano, et al., 2012). Nevertheless, the legislator framework requires moving its spotlights upon another aspect as well, namely the liability of the automated vehicle's operation and the allocation of responsibilities when automated vehicles are in operation (SMART, 2011). Finally, Litman (2015) has identified additional costs and inabilities of the automated vehicles, regarding security and privacy concerns, social equity concerns and reduced employment and business activity.

Taking a step further, in the given literature there is no clear research on the level of success of this new mode, regarding the potential demand that would be captured, not only for the automated vehicles, but also the effects on other mode choices. The focus, so far, has been mainly on the technical aspects and operations of this new mode, while the investigation of the potential demand of this new mode has been neglected, with few exceptions ((May, et al., 2012), (Kocks, et al., 2014)). The operation of the automated vehicles is promoted so far through pilot programs or case studies (chapter 1.1.3), though, the operational framework regarding the role of this mode into the existing network is not clarified or investigated thoroughly yet. For instance, are the automated vehicles operating as main or access/egress mode choice? If operating as access/egress modes, for which main mode? Are the automated vehicles parts of the private transport sector as access/egress mode choice for car trips, or is the focus on serving the last mile trips for PT mode choices such as train trips? On which train stations could be the focus: on all possible or to low/medium demand ones, in which the automated vehicles could be established and support the existing PT public transport network and generate probably more train demand? All these questions are not answered yet.

A crucial point regarding the automated vehicles is what are the costs and benefits that the supply and demand of the new system would generate to the associated stakeholders. Although many researchers tried to capture the costs and benefits of the new system ((Kerr, et al., 2005), (May, et al., 2012), (CityMobil2, 2015)), no existing literature has tried to elaborate on costs and benefits in a broader framework. For instance, what are the (monetary) effects from the operation of the automated vehicles on travel times, fares and environmental impacts for the new mode, as well as for other modes (car, bicycle, pedestrians, PT)? What are the effects for other stakeholders, such as the society, the government and other PT operators? The questions remain without an answer.

All the above and many more related to automated vehicles, are potential fields of interest for researchers to investigate. In the next part, the choice of the framework in which this project is defined is presented and explained, including also the identification of the problem, which this research is handling.

#### 1.2 Problem Background

All the researches and case studies that are described in chapters 1.1.1-1.1.3, are aiming on familiarizing the academic, political, social and economic community of the automated vehicles as both public and private mode choice. However, their main approach is based on the technical characteristics and aspects of the automated vehicles ((Berns & Puttkamer, 2009), (Guzman, et al., 2012), (Hoogendoorn, et al., 2013)) and the methodologies to incorporate them to the current transport network in terms of infrastructure, land use distribution, capacity and route adaptations ((Yigitcanlar, et al., 2008), (Young, et al., 2009), (May, et al., 2012), (Zhang Y., 2013)), as discussed in chapter 1.1.

Nevertheless, there are a lot of other aspects of this exact same topic that are not covered yet by existing literature, as elaborated in chapter 1.1.4. Among these missing aspects, are also the investigation of the potential demand of the automated vehicles, and more specifically, as access/egress mode for train trips. Regarding the use of automated vehicles as access/egress modes for train trips, no investigation has been made so far that would identify the interaction between those two mode systems and if the operation of the automated vehicles could generate more train trips, especially for the low/medium demand train stations. Finally, from the current literature, there is no investigation reflecting the automated vehicles.

Based on all the above, the main question is how can the potential of implementing the automated vehicles as access/egress mode choice for train trips be assessed in a regional setting in the Netherlands, in terms of demand (of the automated vehicles, the respective train station and the rest modes) and costs-benefits of the associated system (affected by the automated vehicles' operation). This question is reflected on two main aspects. Firstly, what methodology, and respective criteria, is necessary in order to identify the highest potential regional setting (train station-zones-routes), so that the automated vehicles could successfully operate as access/egress mode for train trips, especially for low/medium demand train stations? And secondly, what are the potential effects of implementing the automated vehicles in a regional setting, in terms of potential demand and costs-benefits? Taking this comment into account, the identification of the highest potential train station, associated zones that would be served by automated vehicles around the selected train station and the final routes for the automated vehicles are of crucial importance, as well as the evaluation of implementing the automated vehicles into the existing network.

This problem is complex because it has as prerequisite the incorporation of three different aspects (Figure 1.3). Firstly, it requires the combined and successful integration of three transport and spatial levels (train station, zones and routes) in order to implement the new mode into the regional setting. Secondly, it is important to determine the effects in terms of demand, derived from the implementation of the automated vehicles. And finally, the monetarization of all involved costs and benefits of all the important stakeholders associated is necessary, in order to determine the final cost-benefit effects of the introduction of the new mode.



Figure 1.3: Problem aspects

#### **1.3 Research Questions and Objectives**

Based on the problem background described above, there is one main research question, capturing the technical aspect of the problem, which formulates the purposes of this project:

#### What methodology can be developed for the systematic scanning and evaluation of areas in order to identify potential for highly automated vehicles as egress/access modes for *low/medium demand train stations?*

This question creates the need for three more sub-questions that would clarify the research question and would provide further input for the general approach of the project:

What are the main identification and evaluation criteria to be used in the methodology that would determine the highest potential train station-zones-routes combination for successfully introducing the fully automated vehicles?

How can this new mode be applied to the current model of the city and province of Utrecht?

What are the outcomes of the case study, after the implementation of the new mode in the province of Utrecht?

The objectives are classified based on the different parties that need to be satisfied by this project, namely TUDelft and Goudappel Coffeng. So, these objectives are described below:

- Determination of identification and evaluation criteria for the methodology.
- Application of the methodology to a case study.
- Successful modelling of the automated vehicles, with as realistic input data as possible.
- Generation of demand (for automated vehicles and related train station).

Decrease of general costs and increase of general benefits (positive cost-benefit ratio).

#### **1.4 Scientific Contribution**

Thus, after the literature study that has been conducted so far and the gaps identified in chapter 1.1.4, the two main points that are not captured from other researches and are elaborated in this project are:

- Investigation of potential demand for automated vehicles as access/egress mode for train trips: No researches have been so far generated for the public transport network, regarding the investigation of potential demand for automated vehicles as access/egress mode for train trips, and especially for low/medium demand train stations and their impacts in public and private transport demand in general. This project will develop a methodology that is able to identify the highest possible potential, in terms of demand, for the automated vehicles.
- Introduction of a Cost-Benefit Analysis (CBA) for the entire system influenced by the automated vehicles as an evaluation tool for the implementation of the new mode: So far, the available literature regarding the costs and benefits of the automated vehicles and their operation is focusing only on the financial aspects of this new operation, without taking into account broader stakeholders/perspectives such as the passengers and the society. Thus, this research will incorporate this general CBA into the main methodology, together with the previous point, as important evaluation tool for the final implementation of the new mode.

These two points are going to be investigated and applied in this project and are the scientific contribution to the general literature regarding the fully automated vehicles.

#### **1.5 Case Study Choice: City and Province of Utrecht**

For the purposes of this project, a need arises for a specific case study that could be used as input for the application of the methodology. The case study of this project is the city and province of Utrecht (Figure 1.4). Goudappel Coffeng provided the respective model in the OmniTRANS environment. The model is a detailed model in terms of access/egress modes (the access/egress modes modelled are the car, the bicycle and the pedestrians). The main spatial characteristics that are examined from the province of Utrecht in this project are:

- Train Stations: All the train stations within the boundaries of the province of Utrecht are part of the investigation and are used as input for the identification of the highest potential train station.
- Zones: All the associated zones to the respective investigated train station are used as input for the identification of the highest potential zones.
- <u>Routes:</u> All routes that connect the investigated train station with the respective zones are used as input for the final design of the highest potential routes that the automated vehicles will use.



Figure 1.4: Province of Utrecht

#### 1.6 Scope of Project

The project that is elaborated here is framed in specific borders, which define the scope that is used. These borders are presented below:

- Level of Automation: The level of automation assumed for the automated vehicles in this project is Level 4, according to the definition provided by SAE (2014).
- Regional Setting Choice: The choice regarding the regional setting, in which the automated vehicles are implemented, is inside the borders of the Netherlands, and more specifically, the province of Utrecht.
- Mode Choice: The automated vehicles are assessed in this project as access/egress mode choice for train trips.
- Train Station Demand: The implementation of the automated vehicles is focused on train stations with low/medium demand. This choice is based on the approach decided in this project, namely to investigate the influence of the automated vehicles as access/egress mode choice to the train trip volumes.
- Time Frame of the Project: The base year of this project is 2010 (the data available are from this year), while the time horizon is until 2040. The choice of the 30-years' time horizon is based on a) the lifetime of the automated vehicles and b) the incentive to investigate the operational costs and benefits of the automated vehicles until the end of their lifetime.

#### **1.7 General Thesis Approach**

The general approach that is used for this project is reflected in the following diagram (Figure 1.5). With this approach, the clear steps for the entire project are presented as a general guideline. The starting point is the determination of the research question, based on the literature and missing points that are identified, as already elaborated in chapter 1.3. Chapter 2 is elaborating on the main methodology of this research. The main three parts of the methodology are a) PART A: the identification/design process for three transport network levels (train station, zone and route levels), b) PART B: the determination of the cases, namely the highest potential train station-zones-routes combinations for the implementation of the automated vehicles and c) PART C: the evaluation process of each case in terms of demand and systematic costs-benefits. During the first part of the methodology (identification/design process), two important analyses are included: the sensitivity analysis for the zone level and the validation of the train station-zone levels.

In chapter 3, the application of the methodology is presented in the province of Utrecht. In this chapter, the first two parts of the methodology (PART A and B) are applied (identification/design process with respective criteria per level and determination of train station-zones-routes cases), as well as the determination of the model setup per case, so that the automated vehicles are implemented to the OmniTRANS model of Utrecht, according to the outcomes of PART A and B. Moreover, in chapter 4 the evaluation process of the methodology (PART C) is applied per case determined in chapter 3. The evaluation process involves the application of demand-related criteria and cost-benefit analysis criteria for the broader system influenced, framed in a systematic CBA. The final step of the general approach is the elaboration on the conclusions and recommendations of the entire research, presented in chapter 5.



Methodology for assessing the potential of using automated vehicles as an access/egress mode for train trips in a regional setting-An application to the province of Utrecht

# 2 METHODOLOGY

#### 2.1 Introduction

In chapter 1, the literature review revealed the research questions of this project, on which the entire study is based. This chapter is aiming to develop and describe the methodology that is further used in the application case study of the province of Utrecht in chapter 3 regarding the automated vehicles and their potential of implementation. Zooming in to the methodology, it is consisted of 3 main parts (Figure 2.1).

#### PART A: Identification/design process

Part A involves the identification and design process, divided into 3 levels: the train station identification level, the zone identification level and the route design level. The goal of this part is the determination of the highest potential train station, associated zones and connecting routes that would maximize the potential demand and operational benefits for automated vehicles. Each of these levels consists of certain criteria and constraints, which are associated to each level and are elaborated in detail in chapters 2.2.1, 2.2.2 and 2.2.3. Also in this part, two important processes are included: the sensitivity analysis in the zone level and the validation of the train station and zone level (see chapter 2.2.4). The purpose of these processes is to assure the robustness and the validity of the choices during the train station and zone identification levels.

#### PART B: Determination of cases

Part B of the methodology refers to the determination of the highest potential train stationzones-routes combinations/cases, based on the outcomes of Part A. The purpose of this part is to highlight the need for different cases that are further evaluated in Part C of the methodology. The choice of the zones and the routes that would connect them with the selected train station are dependent on different factors. Each researcher/modeller/policy maker is obliged to decide upon the number of zones that eventually are applied to the case study, the operational characteristics of the existing network that the automated vehicles might use and the potential incorporation of other aspects of the network, in which the automated vehicles have advantages over other motorised modes. All these potential choices for the determination of the final cases are in detail described in chapter 2.3. The outcome is a set of highest potential train station-zones-routes combinations, which are further examined in Part C of the methodology.

#### PART C: Evaluation process

The cases derived in PART B are evaluated separately and in comparison with each other in order to determine the most efficient and viable combination among all. These different combined cases (train station-zones-routes combinations) are examined according to 2 sets of evaluation criteria: the pure demand-related criteria and the cost-benefit analysis criteria. In the first set, the train station-zones-routes combinations are evaluated regarding their demand outcomes for the new mode (AV users) and for the general mode changes in the network (train users, access/egress mode choices from/to the selected train station and modal split in the selected zones). In the second set, the criteria are reflecting the effects on the costs and benefits of the new mode into the network, taking into account different stakeholders (Cost-Benefit Analysis). For this reason, the criteria are general and try to capture the influence to the different stakeholders/perspectives involved (investment effects, fare effects, externality cost effects, levy effects, operational cost effects and travel time effects). Both criteria sets are in more detail described in chapters 2.4.1 and 2.4.2.

It is important to highlight that the methodology is not technology driven, which means that the technical characteristics of the automated vehicles and their infrastructural demands do not depend on the current technologies available, but instead, the automated vehicles are applied into the methodology (and latter into the case study) without any technological constraints. This choice is made taking into account that the actual application of such a mode is going to be realized after 10-15 years, assuming that the technology at that period will be developed rapidly. Finally, as already discussed in chapter 1.6, the entire project is based on the requirement to investigate the potential of automated vehicles as access/egress mode for low/medium train stations, so the approach, regarding the selection of the train stations, zones and routes, is in respect to this requirement.



Figure 2.1: Methodology

#### 2.2 PART A: Identification/Design Process

The main and starting part of the methodology is the identification and design framework, namely the determination of criteria that are used for each of the two identification levels and the design level: train station identification level, zone identification level and route design level. This framework is reflecting a top down approach (Figure 2.1). The starting point is the determination of 3 identification criteria for the train station level (the last criterion involves 5 constraints) regarding the total of the train stations inside the boundaries of the investigated area with the objective of finding the highest potential train station. The criteria used in this level are excluding criteria, meaning that each criterion is applied to the train stations in order to exclude train stations that are not complying with each of these criteria and finally conclude to the train station that satisfies all 3 criteria (including the constraints of the third criterion). This step is followed by the creation of 5 identification criteria for the associated zones of the chosen train station from the previous step, in order to find, among all of them, the highest potential ones. In this level, the criteria are applied simultaneously to all zones associated to the chosen train station, which zones are evaluated for these criteria and the outcome is the highest potential zones. Finally, the route level is the concluding step that is considered as design level, in which the automated vehicles are applied, connecting the selected train station with each chosen zone from the previous step. The route design level involves also 5 decision criteria, aiming to find the highest potential route(s). Again, the application of all criteria is performed simultaneously as in the previous level.

The methodology is aiming for combinations of train station-zones-routes that would lead to the highest possible potential for successfully implementing the automated vehicles as access/egress mode for train stations in terms of demand and costs-benefits. Furthermore, the choice of the highest potential train station is preceding the choice of highest potential associated zones and sequentially, of the highest potential routes. Finally, each of these decision criteria are further described for each level in chapters 2.2.1, 2.2.2 and 2.2.3 with their respective mathematical formulations and the purpose of using each criterion.

#### 2.2.1 Identification Level: Train Station

The objective of the first level of the identification process is the selection of the highest potential train station. Since the focus is on low/medium demand train stations, the 3 criteria used are valued in respect to this requirement. The third criterion of this level is referring to zone characteristics of each train station. So, in order to capture these characteristics, 5 constraints are created within this criterion, which are applied simultaneously to all associated zones of the train stations that derived from the application of the previous 2 criteria. After the application of the 5 constraints, and therefore, the satisfaction of criterion 3, the final train station choice is revealed. All the criteria and constraints related to the train station identification level, their respective mathematical formulations and the reason for using each criterion are presented in this chapter. For reasons of simplicity, all the general notations that are used for the criteria of this level are summarised in Table 2-1.
Table 2-1: General notations of train station level

**General Notations of the Train Station Analysis Level** 

#### <u>Sets</u>

 $I = \{1, ..., i, ..., N_s\}$ : Set of all train stations within the case study area, where:  $N_s = Total$  number of train stations

 $I_1 = \{1, ..., i, ..., N_{s1}\}$ : Set of train stations that are selected using **criterion 1.1**, where:  $N_{s1} = Total$  number of train stations that are selected using **criterion 1.1** 

 $I_2 = \{1, ..., i, ..., N_{s2}\}$ : Set of train stations that are selected using **criterion 1.2**, where:  $N_{s2} = Total$  number of train stations that are selected using **criterion 1.2** 

 $J = \{1, ..., j, ..., N_z\}:$ 

Set of zones within an accessibility radius r around all train stations  $i \in I_2$ , where: r = Accessibility radius around each train station  $i \in I_2$ 

 $N_z = Total$  number of zones within the accessibility radius r around all train stations  $i \in I_2$ 

 $J_1 = \{1, ..., j, ..., N_{z1}\}$ : Set of zones that are selected from **constraint 1.1**, within an accessibility radius r around each investigated train station  $i \in I_2$ , where:,  $N_{z1} = Total$  number of zones that are selected from **constraint 1.1**, within the accessibility radius r around each investigated train station  $i \in I_2$ 

 $J_2=\{1,\ldots,j,\ldots,\,N_{z2}\}$ 

: Set of zones that are selected from **constraint 1**.2, within an accessibility radius r around each investigated train station  $i \in I_2$ ,

where:,  $N_{z2}$  = Total number of zones that are selected from constraint 1.2, within the accessibility radius r around each investigated train station  $i \in I_2$ 

 $J_3 = \{1, ..., j, ..., N_{z3}\}$ : Set of zones that are selected from **constraint 1.3**, within an accessibility radius r around each investigated train station  $i \in I_2$ , where:,  $N_{z3} = Total$  number of zones that are selected from **constraint 1.3**, within the accessibility radius r around each investigated train station  $i \in I_2$ 

 $J_4 = \{1, ..., j, ..., N_{z4}\}$ : Set of zones that are selected from **constraint 1.4**, within an accessibility radius r around each investigated train station  $i \in I_2$ , where:,  $N_{z4} = Total$  number of zones that are selected from **constraint 1.4**, within the accessibility radius r around each investigated train station  $i \in I_2$ 

 $M = \{1, ..., m, ..., 4\}$ : Set of access/egress modes from train station  $i \in I_1$ , where: 1 = Walking, 2 = Cycling, 3 = Driving, 4 = PT

 $M' = \{1, ..., m, ..., 3\}$ : Set of main mode choices of zones  $j \in J$  that are located around train stations  $i \in I_2$ , where: 1 = Cycling, 2 = Driving, 3 = PT

 $P = \{1, ..., p, ..., 5\}$ : Set of trip purposes of zones  $j \in J$  that are located around train stations  $i \in I_2$ , where: 1 = Work, 2 = Business,

3 = Education, 4 = Shopping, 5 = Others $K = \{1, ..., k, ..., K\}$ : Set of bus lines serving zones j  $\in J_3$  that are located around train stations  $i \in I_2$  $F = \{1, ..., f, ..., F\}$ : Set of frequencies (vehicles/hour) per day of bus lines k  $\in \mathbf{K}$  serving zones  $j \in J_3$  that are located around train stations  $i \in I_2$  $S = \{1, ..., s, ..., S\}$ : Set of bus stops used by bus lines  $k \in K$  serving zones j  $\in J_3$  that are located around train stations  $i \in I_2$  $W = \{1, ..., w, ..., W\}$ : Set of on – board passengers per day for frequencies f  $\in F$  for bus stops  $s \in S$  used by bus lines  $k \in K$  serving zones j  $\in J_3$  that are located around train stations  $i \in I_2$ Variables TS = Final train station choice $P_{MaxTotal_i} = Maximum potential of train station i$  $\in$  *I* by accomplishing all 3 criteria  $TT_i = Number of daily train trips of train station i, \forall i \in I$  $TT_i^m$  = Number of daily trips of access/egress mode m  $\in M$  from train station  $i, \forall i \in I_1$  $P_{\max_{i,i}} = Zones j$  $\in$  J around train station i with the maximum potential, namely accomplishing all 5 constraints  $ZT_{i,i}^{m,p}$  = Number of daily trips of zone  $j \in J$  that is located around train station i  $\in I_2$ , for mode  $m \in M'$  and trip purpose  $p \in P$  $a_{ii} = 1$  if zone  $j \in J_1$  is associated to train station  $i \in I_2$ , 0 otherwise  $Z_i$  = Number of zones for train station i  $\in I_2$  that are selected from constraint 1.1  $TD_{ii}$  = Shortest travel distance between zone  $j \in J_2$  and train station  $i \in I_2$  $BS_{i,j,k} = Daily$  bus service level (daily average on - board passengers) of all bus lines  $k \in \mathbf{K}$  serving zone j  $\in J_3$  that is located around train station  $i \in I_2$  $NBL_{i,i,k} = Number of bus lines k \in K$  serving zone j  $\in J_3$  that is located around train station  $i \in I_2$  $F_k$  = Frequency (vehicles/hour) of bus line  $k \in K$  serving zone j  $\in J_3$  around the investigated train station  $i \in I_2$  $OB_{f,k,s} = On - board passengers for frequency f \in \mathbf{F}$  of bus line  $k \in \mathbf{K}$  in bus stop s  $\in S$  serving zone  $j \in J_3$  that is located around train station  $i \in I_2$ 

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 $Z_{max} = Maximum$  number of zones  $j \in J_4$  around train station  $i \in I_2$  among all zones  $j \in J_4$  of all train stations  $i \in I_2$ 

 $\alpha_1 \dots \alpha_8 = Upper \text{ or lower bound values of criteria}$ 

The general objective of the first level is aiming to find the highest potential train station, with criteria associated to demand aspects, and is determined below:

**OBJECTIVE:** Find the highest potential train station for the implementation of the automated vehicles.

$$TS = P_{MaxTotal_i}, \qquad i \in I \tag{1.1}^1$$

s.t.3 criteria (below)

In order to satisfy this objective, three excluding criteria are developed, explained mathematically and for their purpose of use:

<u>**Criterion 1.1:**</u> Choose train stations with low/medium daily train trip volumes (access and egress trips).

**Mathematical Formulation:** Total daily train trips of train station  $i \in I$  should be less or equal to a maximum value of train trips per day.

$$TT_i \le \alpha_1 \operatorname{traintrips}/\operatorname{day}, \ \forall \ i \in I$$
 (1.2)

**Purpose of criterion 1.1:** Based on the daily train trips, choose only the train stations that have volumes lower or equal to a maximum value that is determined within the case study.

**<u>Criterion 1.2</u>**: Choose train stations that filter access/egress mode demand.

**Mathematical Formulation:** Access/egress daily trips by mode  $m \in M$  from/to train stations  $i \in I_1$  with high car volumes, low bus volumes and low bicycle volumes.

$$TT_i^{m=3} \ge \alpha_2, \quad \forall \ i \in I_1, \ m \in M \tag{1.3}$$

$$TT_i^{m=4} \le \alpha_3, \quad \forall \ i \in I_1, \ m \in M \tag{1.4}$$

$$TT_i^{m=2} \le \alpha_4, \quad \forall \ i \in I_1, m \in M \tag{1.5}$$

**Purpose of criterion 1.2:** Used for identification of potential "competitors" of the automated vehicles (the bicycles), as well the potential modes that could be replaced by automated vehicles (cars and buses). This means that high car usage and low bus/bicycle volumes could

<sup>&</sup>lt;sup>1</sup> The first part of the numbering of each equation refers to the level that this equation is associated (level 1, 2 and 3), while the second part is sequential, starting from equation 1 to the final equation of level 3.

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be an indicator of low PT and bicycle volumes as access/egress modes, which means extra "plus" for the automated vehicles.

The last criterion is capturing zone-related characteristics of the associated train stations, and its satisfaction aims to identify the highest potential zones of one train station, among all investigated train stations derived from criterion 1.2. For all these reasons, 5 constraints are developed, which are satisfying criterion 1.3. So, criterion 1.3 and its respective constraints are further analysed below:

<u>**Criterion 1.3:**</u> Choose the maximum potential train station, based on the maximum potential zones around it.

**Mathematical Formulation:** Train station  $i \in I_2$  that includes, within its accessibility radius r (Figure 2.2), zones  $j \in J_1$  that have the maximum potential in terms of accomplishing 5 zone-related constraints.

$$TS = P_{\max_{i,j}}, \qquad i \in I_2, j \in J$$
(1.6)



*s.t.5 constraints (below)* 

Figure 2.2: Example of accessibility radius around a train station

**Purpose of criterion 1.3:** The final choice of train station is related to the candidate zones associated with the train station. In order to determine the maximum potential train station, the maximum potential zone-demand is important to be defined, according to 5 constraints that determine, among all train stations, the zones that satisfy all 5 constraints and lead to the final choice of the train station.

## Constraints for criterion 1.3

In order to determine the maximum potential train station, 5 constraints are determined, which are all connected to zone-related characteristics of the train stations derived from criterion 2. These constraints are applied simultaneously to each train station and associated zones, so that the final outcome is the highest potential train station, satisfying all 5 constraints, and therefore, criterion 3.

*Constraint 1.1:* Choose zones that filter mode/purpose demand.

**Mathematical Formulation:** Zones  $j \in J$  of train station  $i \in I_2$  that have:

1) High number of total daily trips for all main modes  $m \in M'$  and for all trip purposes  $p \in P$ 

$$\sum_{\substack{m \in M' \\ p \in P}} ZT_{i,j}^{m,p} \ge \alpha_5, \qquad \forall \ i \in I_2, \forall \ j \in J$$
(1.7)

2) High number of total daily car trips for all trip purposes  $p \in P$ 

$$\sum_{\substack{m=2\\p\in P}} ZT_{i,j}^{m,p} \ge \alpha_6, \qquad \forall \ i \in I_2, \forall \ j \in J$$
(1.8)

3) High number of total daily trips for all main modes  $m \in M'$  and for work/business purposes

$$\sum_{\substack{m \in M' \\ p \in \{1,2\}}} ZT_{i,j}^{m,p} \ge \alpha_7, \qquad \forall \ i \in I_2, \forall \ j \in J$$
(1.9)

4) Low number of total daily PT trips for all trip purposes  $p \in P$ 

$$\sum_{\substack{m=3\\p\in P}} ZT_{i,j}^{m,p} \ge \alpha_8, \qquad \forall \ i \in I_2, \forall \ j \in J$$
(1.10)

**Purpose of constraint 1.1:** High number of total daily trips per zone means high potential demand for automated vehicles. Moreover, high car volumes could be an indicator of possible access/egress dysfunctions due to lack of PT to connect the train stations (see case in Figure 2.3). Furthermore, high number of daily work/business trips could be translated as work/business demand that is an interesting target group for the automated vehicles. Finally, low number of daily PT trips (as main mode) could mean low PT service and more potential for automated vehicles.

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Figure 2.3: Lack of access/egress PT modes

Constraint 1.2: Choose zones that are associated to only one train station.

**Mathematical Formulation:** Zone  $j \in J_1$  that is associated only to train station  $i \in I_2$ .

$$Z_i = \sum_{j \in J_1} a_{ij} \tag{1.11}$$

$$a_{ij} = \begin{cases} 1, if \ TD_{ij} \le TD_{kj}, k \in I_2/\{i\} \\ 0, otherwise \end{cases}, \quad \forall \ i \in I_2, \forall \ j \in J_1 \end{cases}$$
(1.12)

where:

 $TD_{ij}, TD_{kj} = Shortest travel distances between zone <math>j \in J_1$  and train stations  $i, k \in J_1$  $I_2$ 

Purpose of constraint 1.2: Select the zones that are associated to only one train station, among all available train stations.

Constraint 1.3: Choose zones that are located further than walking/cycling distance from train stations.

**Mathematical Formulation:** Zone  $j \in J_2$  that is at least 1 km away from the investigated train station  $i \in I_2$ .

$$TD_{ij} \ge 1km, \quad \forall \ i \in I_2, \forall \ j \in J_2 \tag{1.13}$$

Purpose of constraint 1.3: The distance of 1km is chosen in order to prevent the selection of zones that are accessible by pedestrians and cyclists (the choice of distance is based on the research of Zhang, et al. (2015)).

Constraint 1.4: Choose zones with low daily bus service level (daily average of on-board passengers for all bus lines per zone).

**Mathematical Formulation:** Zone  $j \in J_3$  around train station  $i \in I_2$  that has low daily bus service level (low daily average of on-board passengers for all bus lines per zone).

$$BS_{i,j} = \frac{\left(\sum_{\substack{w \in \mathbf{W}, f \in \mathbf{F}}(F_k \times OB_{f,k,s})\\s \in S, k \in \mathbf{K}\\i \in I_{2,j} \in J_4\\NBL_{i,j,k}}\right)}{NBL_{i,j,k}} \le \alpha_9, \ \forall \ i \in I_2, \forall \ j \in J_3, \forall \ w \in \mathbf{W}, \forall \ f \in \mathbf{F}, \forall \ s \in \mathbf{S}, \forall \ k \in \mathbf{K}$$
(1.14)

**Purpose of constraint 1.4:** By selecting zones with low daily bus service level, there is room for potential replacement of current bus lines by automated vehicles or operation of automated vehicles for generating PT demand.

*Constraint 1.5:* Choose the train station with the highest number of potential zones.

**Mathematical Formulation:** Number of zones  $j \in J_4$  around train station  $i \in I_2$  that is the maximum.

$$Z_{i,j} = Z_{max}, \quad i \in I_2, j \in J_4$$
 (1.15)

*Purpose of constraint 1.5:* Higher possibilities of capturing demand for automated vehicles by selecting the train station with the maximum number of potential zones.

The application of all 3 criteria, and the 5 constraints of the last criterion, is satisfying the main objective of this identification level, namely the choice of the highest potential train station.

#### 2.2.2 Identification Level: Zone

After the selection of the train station with the highest potential of the previous level, the zone level requires the determination of the highest potential zones that are associated to the selected train station. After the implementation of criterion 1.3 of the previous level, a pre-selection of potential zones has been already conducted, based on some zone-related characteristics that are captured by the 5 constraints within criterion 1.3. These zones are associated to the train station that has been selected in the previous level. So, this zone identification level (Figure 2.1) requests, as general objective, the clear determination of the maximum potential zones among all the zones pre-selected in the train station level. This choice, thus, has as prerequisites 5 criteria, which are simultaneously applied to the zones. Furthermore, an evaluation and ranking process of the zones is realised, based on these criteria, aiming to reveal the maximum potential zones associated to the selected train station. In this part, all criteria are developed with their respective mathematical formulations and purpose of usage, as in the train station level. Finally, Table 2-2 summarizes all the associated notations of the 5 criteria of the zone level.

Table 2-2: General notations of zone level

#### **General Notations of the Zone Analysis Level**

#### <u>Sets</u>

 $J' = \{1, \dots, j, \dots, N_{z'}\}:$ Set of zones within an accessibility radius r around the selected train stations S, where: S = Selected highest potential train station as outcome of the train station level, r = Accessibility radius around train station S,  $N_{z'}$  = Total number of zones within the accessibility radius r around train stations S  $M = \{1, ..., m, ..., 3\}$ : Set of main mode choices of zones  $j \in$ I' that are located around train station S, where: 1 = Cycling, 2 = Driving, 3 = PT $P = \{1, ..., p, ..., 5\}$ : Set of trip purposes of zones  $j \in J'$  that are located around train station S, where: 1 = Work, 2 = Business, 3 = Education, 4 = Shopping, 5 = OthersVariables  $Z_S$  = Number of zones for train station S  $P_{\text{MaxTotal}_{S,i}} = Zones j$  $\in$  J' around train station S with the maximum potential, namely accomplishing all 5 constraints  $ZT_{S,j}^{m,p}$  = Number of daily trips for zone  $j \in J'$  of train station S, for main mode m  $\in M$  and purpose  $p \in P$  $\alpha_{10} \dots \alpha_{14} = Upper \text{ or lower bound values of criteria}$ 

The main objective of the zone level is to find the maximum potential zones that are associated to the selected train station and would maximize the potential demand for automated vehicles. This selection is performed for the zones derived after the application of criterion 1.3 of the train station level.

**OBJECTIVE:** Choose the highest potential zones to connect them with the highest potential train station by automated vehicles.

$$Z_S = P_{\text{MaxTotal}_{S,j'}} \quad j \in J'$$
(2.16)

s.t. 5 criteria (below)

Based on this objective, the criteria used for accomplishing this goal are elaborated below, with all the respective mathematical formulations and usage purposes for each criterion:

**<u>Criterion 2.1</u>**: Choose zones with high daily trip volumes (productions/attractions).

**Mathematical Formulation:** Zone  $j \in J'$  of train station s with high number of total daily trips for all main modes  $m \in M$  and for all trip purposes  $p \in P$ 

$$\sum_{\substack{m \in M \\ p \in P}} ZT_{S,j}^{m,p} \ge \alpha_{10}, \qquad \forall j \in J'$$
(2.17)

**Purpose of criterion 2.1:** High number of total daily trips per zone means high potential demand for automated vehicles.

**<u>Criterion 2.2:</u>** Choose zones with low bicycle share in total trips.

**Mathematical Formulation:** Zone  $j \in J'$  of train station S with low daily bicycle trips for all purposes  $p \in P$ , compared to the total daily trips per zone.

$$\sum_{\substack{m=2\\p\in P}} ZT_{S,j}^{m,p} \le \alpha_{11}, \quad \forall j \in J'$$
(2.18)

**Purpose of criterion 2.2:** By identifying the zones with low bicycle volumes, the competition for the automated vehicle by the bicycle is low, which means more potential demand could be captured by the new mode.

**<u>Criterion 2.3</u>**: Choose zones by filtering the work/business bicycle trips.

**Mathematical Formulation:** Zone  $j \in J'$  of train station S with low number of daily bicycle trips for work/business purposes.

$$\sum_{\substack{m=2\\ p \in \{1,2\}}} ZT_{S,j}^{m,p} \le \alpha_{12}, \ \forall j \in J'$$
(2.19)

**Purpose of criterion 2.3:** The focus on the work/business trips is because of the interesting population group that working/business people are, while low daily bicycle volumes allows the development of the automated vehicles with low competition by bicycles.

**<u>Criterion 2.4</u>**: Choose zones with low bicycle share, compared to the car and PT.

**Mathematical Formulation:** Zone  $j \in J'$  of train station S with low number of daily bicycle trips, compared to the daily car and PT zone trips, for all purposes  $p \in P$ .

$$\frac{\sum_{\substack{p \in P \\ p \in P}} ZT_{S,j}^{m,p}}{\left(\sum_{\substack{m=1 \\ p \in P}} ZT_{S,j}^{m,p} + \sum_{\substack{m=3 \\ p \in P}} ZT_{S,j}^{m,p}\right)} \le \alpha_{13}, \ \forall \ j \in J'$$
(2.20)

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**Purpose of criterion 2.4:** The purpose of this criterion is to determine the share of the bicycle, compared to the car and PT, namely the level of competition of the bicycle towards the other two main mode choices of each zone. The low levels of competition of the bicycle mean that the automated vehicles could be established into the network as part of the PT, and not compete with the bicycle. At the same time, the automated vehicles could aim for capturing existing car demand.

<u>**Criterion 2.5:**</u> Choose zones by filtering the work/business bicycle trips, compared to the car and PT trips.

**Mathematical Formulation:** Zone  $j \in J'$  of train station S with low number of daily bicycle trips, compared to the daily car and PT zone trips, for work/business purposes.

$$\frac{\sum_{\substack{p \in \{1,2\}}} ZT_{S,j}^{m,p}}{\left(\sum_{\substack{m=1\\p \in \{1,2\}}} ZT_{S,j}^{m,p} + \sum_{\substack{m=3\\p \in \{1,2\}}} ZT_{S,j}^{m,p} + \sum_{\substack{m=3\\p \in \{1,2\}}} ZT_{S,j}^{m,p}\right)} \le \alpha_{14}, \ \forall \ j \in J'$$
(2.21)

**Purpose of criterion 2.5:** The purpose of this criterion is the same as the previous criterion, but additionally, the focus is on the main interesting population group for the automated vehicles, namely the working/business people.

The evaluation, in order to rank the potential zones according to all 5 criteria, is determining the maximum potential zones, and thus, the satisfaction of the objective set in the beginning of this part.

This process reveals the maximum potential zones, ranked with each other. However, the number of zones that would be applied in the end for the operation of the automated vehicles depends on different decision making processes. This means that the researcher/modeller/policy maker that is using this methodology is free to choose which zones to apply in each case study: could be all highest potential zones or the highest ranking ones or only the maximum potential zone out of all the highest potential zones or apply all possible zone combinations at the same time. This decision making could be handled through different cases, which is further elaborated in chapter 2.3.

## 2.2.3 Design Level: Route

The third level, which is the design level of the methodology (Figure 2.1), has as basic objective the determination of the routes that would connect the selected train station and the zones chosen in the previous 2 identification levels (for all possible zone cases as is explained in chapter 2.3). Again, the route choice is dependent on 5 criteria that are simultaneously applied and their application is aiming to satisfy the main objective of this level. All criteria are explained in a mathematical manner, provided also with reasoning for choosing these criteria in the design level. Finally, Table 2-3 represents the total notations that are used for the mathematical formulations of each criterion.

Table 2-3: General notations of route level

General Notations of the Route Design Level
<u>Sets</u>
$J'' = \{1,, j,, N_{z''}\}$ : Set of zones that are selected from <b>zone level</b> within an accessibility radius r around the selected train stations S,

#### where:

S = Selected highest potential train station as outcome of the **train station level**, r = Accessibility radius around train station S,

$$N_{z^{\prime\prime}}$$

= Total number of zones that are selected from **zone level** within the accessibility radius r around train stations S

 $\mathbf{R} = \{1, ..., r, ..., R\}$ : Set of direct routes that connect train station S with zones j  $\in I''$ 

 $W = \{1, ..., w, ..., 2\}$ : Set of directions of route r  $\in \mathbf{R}$  that connects train station S with zones  $j \in J''$ 

 $L = \{1, ..., l, ..., L\}$ : Set of links of direction  $w \in W$  of route r  $\in \mathbf{R}$  that connects train station S with zones  $j \in J''$ 

 $T = \{1, ..., t, ..., T\}$ : Set of motorized road types of link  $l \in L$  of direction w  $\in W$  of route  $r \in R$  that connects train station S with zones  $j \in J''$ 

#### Variables

 $R_{S,j}$  = Direct routes that connect zones  $j \in J''$  and train station S

 $P_{MaxTotal_{r,S,j}} = Routes \ r \in \mathbf{R}$  that connect train station S and zones j  $\in$  J" and have maximum potential, namely routes that accomplish all 5 criteria  $Z_s = Number of zones j \in J''$  that are connected by route  $r \in \mathbf{R}$  with train station S  $TD_{w,r} = Travel \ distance \ of \ direction \ w \in W \ of \ route \ r \in R$  $L_{w,r} = Link \ of \ direction \ w \in W \ of \ route \ r \in R$  $a_{l,w,r} = 1$  if link  $l \in L$  of direction  $w \in W$  of route r  $\in \mathbf{R}$  is not congested, 0 otherwise  $CV_{l,w,r} = Car \ volumes \ of \ link \ l \in L \ of \ direction \ w \in W \ of \ route \ r \in R$  $C_{l,w,r} = Capacity of link l \in L of direction w \in W of route r \in R$  $\beta_{l,w,r} = 1$  if link  $l \in L$  of direction  $w \in W$  of route r  $\in \mathbf{R}$  is allowing high operational speeds, 0 otherwise  $S_{l,w,r} = Maximum \text{ operational speed of link } l \in L \text{ of direction } w \in W \text{ of route } r \in R$   $\gamma_{l,w,r,t} = 1$  if link  $l \in L$  of direction  $w \in W$  of route r  $\in \mathbf{R}$  is allowing the operation of motorized modes, 0 otherwise  $MRT_l = Motorized road type of link l \in L$  $\alpha_{15}, \alpha_{16} = Upper \text{ or lower bound values of criteria}$ 

The goal of this level is to find the set of routes that are considered as highly potential in terms of not only demand, but also in terms of operational benefits, so that they could connect the selected train station with the selected zones:

**OBJECTIVE:** Choose the highest potential routes that could connect the highest potential train station with the highest potential zones.

$$R_{S,j} = P_{MaxTotal_{r,S,j}}, \qquad j \in J'', r \in \mathbf{R}$$
(3.22)

s.t. 5 criteria (below)

The objective determined above is constraint to 5 criteria that are applied simultaneously to all possible routes that could connect the train station selected with the respective zones chosen:

**Criterion 3.1:** Choose routes that capture maximum demand.

**Mathematical Formulation:** Direct route  $r \in \mathbf{R}$  that connects the train station S with the maximum number of zones  $j \in J''$ .

$$R_{S,j} = MaxZ_{s}, \quad \forall j \in J'', \forall r \in \mathbf{R}$$

$$s.t. \sum_{r \in \mathbf{R}} R_{S,j} = \sum_{j \in J''} Z_{s}$$
(3.23)

**Purpose of criterion 3.1:** Find the lowest number of direct routes with the maximum number of zones that are connected to the train station. In this way, the total travel times are low.

**Criterion 3.2:** Choose routes with travel distances attractive to potential demand.

**Mathematical Formulation:** Route  $r \in \mathbf{R}$  with travel distance per direction  $w \in \mathbf{W}$  less or equal to 7 km.

$$TD_{w,r} \le 7 \ km, \qquad \forall \ w \in W, \forall \ r \in R$$
 (3.24)

Purpose of criterion 3.2: The automated vehicles are used as access/egress modes for train trips, so the lower the travel distance per direction of each route, the lower the travel time, and therefore, the more attractive the automated vehicles become.

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**<u>Criterion 3.3:</u>** Choose routes with specific congestion levels.

**Mathematical Formulation:** Select links  $l \in L$  of direction  $w \in W$  of route  $r \in R$  that are having low congestion ratio (car volumes of link  $l \in L$  in comparison to total link capacity).

$$L_{w,r} = \sum_{\substack{l \in L \\ w \in W \\ r \in R}} a_{l,w,r}$$
(3.25)

$$a_{l,w,r} = \begin{cases} 1, if \ CV_{l,w,r} / C_{l,w,r} \le a_{15} \\ 0, otherwise \end{cases}, \quad \forall \ l \in L, \forall \ w \in W, \forall \ r \in R \end{cases}$$
(3.26)

**Purpose of criterion 3.3:** By choosing low congested links, the operational speed of the automated vehicles is not affected, and so, the operational travel time is maximum.

**<u>Criterion 3.4</u>**: Choose routes with specific operational speeds.

**Mathematical Formulation:** Select links  $l \in L$  of direction  $w \in W$  of route  $r \in R$  in which the maximum operational speed is high.

$$L_{w,r} = \sum_{\substack{l \in L \\ w \in W \\ r \in R}} \beta_{l,w,r}$$
(3.27)

$$\beta_{l,w,r} = \begin{cases} 1, if \ S_{l,w,r} \ge a_{16} \\ 0, otherwise \end{cases}, \quad \forall \ l \in L, \forall \ w \in W, \forall \ r \in R \end{cases}$$
(3.28)

**Purpose of criterion 3.4:** By assuring that the maximum operational speed of each link is high, the operational speed of the automated vehicles is also high, and so the total travel times are low.

**<u>Criterion 3.5</u>**: Choose routes that allow the moving of motorized modes.

**Mathematical Formulation:** Select links  $l \in L$  of direction  $w \in W$  of route  $r \in R$  with road type  $t \in T$  that allows the operation of motorized modes.

$$L_{w,r} = \sum_{\substack{l \in L, w \in W \\ r \in R, t \in T}} \gamma_{l,w,r,t}$$
(3.29)

$$\gamma_{l,w,r} = \begin{cases} 1, if \ L_{w,r} = MRT\\ 0, otherwise \end{cases}, \ t \in \mathbf{T}, \forall \ l \in \mathbf{L}, \forall \ w \in \mathbf{W}, \forall \ r \in \mathbf{R} \end{cases}$$
(3.30)

**Purpose of criterion 3.5:** With this criterion, only the links that allow motorized modes are chosen, and so, allow the operation of the automated vehicles as well.

The implementation of all 5 criteria in the route design level aim to provide all possible routes and links on which the automated vehicles could be implemented, so that they could connect the selected train station with the highest potential zones. However, the final selection of the routes and the links for the automated vehicles is a combination that could generate a lot of different options for the modelling part, dependent on the final number of zones selected per case, the operational characteristics of the existing network or the incorporation of special network aspects to the automated vehicles' operation. All these options are further elaborated in chapter 2.3.

## 2.2.4 Sensitivity analysis-validation

In order to check the robustness of the results, as well as the validity of the methodology, a request for a sensitivity analysis and validation has been raised. Both analyses are part of the methodology, and more specifically of the identification/design process (Figure 2.1).

## Sensitivity analysis

The sensitivity analysis, as illustrated in Figure 2.1, is performed during the identification process in the zone level. In this level, the robustness of the zone selection process is determined. The methodology for the zone level is using 5 criteria, through which the zones are evaluated and then ranked, in order to define the highest potential zones that accomplish all 5 criteria and their ranking with each other for these criteria. Nevertheless, the application of the 5 criteria is not pre-defining different weights for each criterion. This means that all of the 5 criteria are equally important for the selection of the highest potential zones.

In order to assure the robustness of the results from the ranking of the zones based on the evaluation criteria of the zone level, different weighting systems for each criterion are used. The application of this analysis is applied in every case study (as it is dependent on the respective available data and input). An example of the sensitivity analysis, performed for the purposes of the methodology, is presented in chapter 3.4.2 in the application case study of this research.

## Validation

Besides the robustness of the choice of the highest potential zones, the validity of the methodology should be checked. So, the validation that is applied for the purposes of this methodology, and for every research using this methodology, is trying to perform the reverse identification process from the one established in the main methodology: starting from the zone level and selecting the highest potential zones, with the respective zone level criteria, would these zone choices and their respective associated train station lead to the same highest potential train station that are identified when starting from the train station identification level.

In short, the validation is aiming to provide valid choices in both identification levels (train station and zone level). The goal is to identify the highest potential train station and

respective zones, even when starting from the zone identification level and then continuing to the train station identification level (reversed action from the one established in the methodology). An example of a validation is presented in the case study of this research (chapter 3.4.2) with the respective input data of both train station and zone level.

# 2.3 PART B: Determination of Cases

The selection of the zones that are connected to the highest potential train station (chapter 2.2.2) is followed by the selection of the routes that would connect the selected train station and zones, out of the total number of potential routes derived from the design route level in chapter 2.2.3. In chapters 2.2.2 and 2.2.3, it is implied that the final zones and routes choices is dependent on different factors. So, the second part of the methodology involves the determination of train station-zones-routes cases that are further evaluated in the last part of the methodology, out of the total number of potential cases. By cases, the possible train station-zones-routes combinations are meant. These combinations, which have as "fixed" the selection of only one train station, but more than one available option regarding the zones and routes to connect with the train station, are dependent on (Figure 2.1):

- The number of potential zones to connect with the selected train station: The criteria used in the zone identification level are determining the ranking between all highest potential zones around the selected train station (zones derived after the completion of the zone level). This ranking defines the number of zones, ranked in the zone level that could be used for the implementation of the automated vehicles. This means that all highest potential zones could be used, or zones that score the highest, compared to the rest, or only the highest scoring zone out of the total number of highest potential zones is finally used. This is a choice determined by each researcher/modeller/policy maker. So, the number of zones selected for the implementation of the automated vehicles into the network, influences, also, the choice of routes that would connect these chosen zones with the selected train station.
- Characteristics of existing network: The usage or not of currently operating bus stops and bus line routes is part of the final route decision that would connect the selected train station and zones: is it beneficial to follow the routes that currently bus lines are operating, with the respective bus stops (if there are any)? Or is it more gainful to determine a new route, and sequentially, new bus stops (for instance use the shortest route that connects the train station with each of the selected zones)?
- Incorporation of special network aspects into the operation of the AVs: Since the automated vehicles are environmentally friendly, the potential routes selected could go through areas that are currently prohibited by motorised vehicles, such as the city centre areas. This provides even more options for the final routing.

All these decisions and options are dependent on the restrictions and expectations of the automated vehicles by any researcher/modeller/policy maker that uses this methodology. This leaves room for different decisions upon the train station-zones-routes combinations/cases that are used and evaluated further in Part C of the methodology.

# 2.4 PART C: Evaluation Process

The third and final part of the methodology is aiming to determine the evaluation criteria for the regional setting, based on the outcomes of the previous two parts (identification/design process and determination of cases) (Figure 2.1). This means that the choices made in the previous two parts request evaluation regarding general criteria that capture the potential demand and costs-benefits of the entire system involved. Though, since this part is considered as crucial for the final choice regarding the highest potential train station-zones-routes combination, and thus, the final choice for implementing the automated vehicles, it includes two main sub parts. The first is the determination of pure demand-related criteria of the new mode and the rest mode choices and the second is the conduction of a cost-benefit analysis framework for the entire system involved (Cost-benefit Analysis). Each of these sub-parts is further explained in chapters 2.4.1 and 2.4.2.

## 2.4.1 Demand-related evaluation criteria

The first step of evaluating the outcomes of PART A and B of the methodology is the determination of criteria related to the outcomes of pure demand, not only for the new mode, but for the entire mode network. The purpose for introducing these criteria is binary: 1) more clear detection of the success of the new mode into the current network, besides monetary criteria as is used by the CBA 2) identification of demand related changes of the transport system on the selected area. So, the proposed evaluation criteria of the methodology are:

- > AV Users (# of passengers)
- Train Users (before and after the implementation of the automated vehicles) (# of passengers)
- Access/egress mode choices from/to the selected train station (before and after the implementation of the automated vehicles) (# of passengers)
- Zones' modal split (for all selected zones before and after the implementation of the automated vehicles) (%)

## 2.4.2 Cost-benefit analysis criteria

The CBA is considered as a powerful tool in order to determine in a relatively satisfying level the efficiency and viability of each combined train station-zones-routes case that is the outcome of PART A and B. Each case is evaluated from a systematic point of view, which means that the criteria of the CBA that are determined here reflect the costs and benefits of different stakeholders (perspectives) involved or influenced by the introduction of the automated vehicles into the existing network. The purpose is to see, for a certain time horizon, how the new transport system is reacting in terms of costs and benefits, as well as in combination with the rest of the modes that are currently operating on the investigated cases, and more specifically the car and the bus.

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The stakeholders (perspectives) that are considered important in this methodology are 5: 1) the passengers, 2) the AV operator, 3) the BTM operator, 4) the government and 5) the society. Here, it is assumed that the AV and BTM operator are different. Based on these perspectives, different criteria are developed that capture the effects (costs or benefits) for each of these stakeholders after the implementation of the automated vehicles. These criteria/effects are:

## 1. Investment Effects:

- a. Construction costs of new AV stops
- b. Purchase of automated vehicles
- 2. Fare Effects:
  - a. Passenger (fare) effects of former BTM users switched to automated vehicles
  - b. Passenger (fare) effects of former car users switched to automated vehicles
  - c. Passenger (fare) effects of other mode users switched to automated vehicles
  - d. AV operator (fare) effects from all AV users
  - e. BTM operator (fare) effects from BTM user changes
- 3. Externality Costs:
  - a. AV externality costs
  - b. Car externality effects

## 4. Operational Cost Effects:

- a. AV operational and maintenance costs
- 5. Levy Effects:
  - a. Levy effects
- 6. Travel Time Effects:
  - a. BTM in-vehicle time effects
  - b. BTM waiting time effects
  - c. Car in-vehicle time effects

This general framework of the CBA can be developed in every case study and be adjusted with the available data and model output in every situation. It is important to highlight that the CBA is evaluating the outcomes of the operation of the automated vehicles in the regional setting they are applied and not all possible effects of the entire network. Further explanation regarding the chosen perspectives, the respective criteria of the CBA and the assumptions used, is presented in chapter 4.3 via the case study outcomes, in order to provide also specific quantitative values for each criterion.

The evaluation process in total (in respect to the demand-related outcomes and the CBA outcomes) is executed for each case, until the entire number of cases is evaluated individually with the base year situation (before the implementation of the new mode) and in comparison with each other. After this process is finished, the highest potential case is chosen that satisfies both evaluation criteria sets in the best possible way.

# 2.5 Conclusions and Recommendations

The methodology developed in chapter 2 is trying to identify, design and evaluate, with respective criteria, the potential of implementing the automated vehicles in a regional

setting as access/egress mode for low/medium demand train station. This methodology consists of three main parts: PART A) identification/design process for three different levels (train station, zones and routes), including sensitivity analysis in the zone level and a validation for the train station and zone levels, PART B) determination of different cases (train station-zones-routes combinations) and PART C) the evaluation of the cases.

This methodology is a stepwise approach, in which the potential regional setting is identified, designed with respective train station-zones-routes combinations/cases and eventually evaluated for each case, so that the most viable and efficient option, among all options examined, would be revealed. The purpose of this methodology is binary: in a microscopic level, to determine the most beneficial, in terms of demand and operational characteristics, train station-zones-routes combinations and in a macroscopic level to investigate these combinations in a more systematic and broader perspective, translating the related effects of the automated vehicles to the system into monetary values. So, Parts A, B and C of the methodology are aiming to capture both levels. In order to test the methodology in real case study, chapters 3 and 4 are presenting the application of the methodology in the province of Utrecht. All three parts of the methodology are applied to the case study chosen and the respective results are developed in both chapters.

However, this methodology could be further elaborated by future researchers in order to incorporate aspects that are not considered here or are not part of the scope of this project.

Starting with possible adjustments of PART A of the methodology, the first constraint of this project is coming from the limitations of the OmniTRANS software and the respective model, based on which, the following points are highlighted for further investigation:

- The criteria used during the identification/design process are based on the abilities of the model of OmniTRANS. For instance, criteria 1.2 and 1.3 of the train station level are both used in order to identify, in an indirect way, the flows between the train stations and the associated zones, data that are not captured directly by the model. These criteria could be incorporated into one, with respective adjustments of the model.
- Additional identification/design criteria/aspects could highlight more the beneficial input of the automated vehicles to the system. These aspects are for example special population groups (older people, children or people with physical inabilities), regional settings with high emission rates or areas with spatial changes, such as new residential areas for families or shopping malls. All these examples are perspectives in which the automated vehicles could be used as potential mode choice.
- Further elaboration on the route design level for eliminating more the potential route sets. The design criteria created in the methodology for the route level are used in order to decrease the number of potential route options by certain standard criteria. Though, still the application of these criteria are leaving room for many route options, as discussed in chapter 2.3. A future research could focus on eliminating the route options more. Possible criteria for this level could be the existence or not of other PT modes on the same route or the land-uses located along the potential routes.

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Furthermore, the methodology is having as basic prerequisites the focus on low/medium demand train stations and the incorporation of the automated vehicles as access/egress modes for train trips into the network. However, these two constraints could be altered in PART A in a future research:

- Regarding the low/medium demand constraint, a future project could investigate the potential for implementing automated vehicles to all possible train stations and not only to the low/medium demand ones.
- The usage of the second constraint, namely the implementation of automated vehicles as access/egress modes for train trips, could be developed in a more general framework. This means, alterations in the identification/design part of the methodology (train station, zones and routes levels) could be applied so that the automated vehicles are investigated as access/egress modes for every PT or car trips, and not only for train trips or even identify the potential of automated vehicles as main mode, rather than only as an access/egress mode.

Moreover, the methodology could be elaborated further in order to improve certain points regarding Parts B and C:

- Regarding the zone cases, more options could be created that would be not only dependent on the number of zones chosen, but also investigate the possible zone combinations that would maximize the potential demand for automated vehicles. For the route cases, routes that would include highways (higher operational speeds for automated vehicles) are possible options.
- Regarding the last part of the methodology and more specifically the CBA, two additional elements could provide better insight of the effects that the automated vehicles have in the associated system:
  - The total travel time effects of the automated vehicles in comparison to the travel times of other modes (especially PT and car). This is a point that requests further investigation in order to identify the potential costs or benefits for AV users in terms of in-vehicle and waiting times, compared to other PT modes or to the in-vehicle travel time of the car users.
  - The incorporation of other modes (besides the BTM and car) into the evaluation process of the CBA. In this way, the entire transport network is examined and potential effects of other modes (bicycle, pedestrians etc.) are taken into account and evaluated, determining their level of influence to the final results.

All these points described above could become the focus on a future research that would try to capture aspects that are not taken into account here, either due to lack of data, inabilities of the model or limited scope of the project.

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# 3 APPLICATION OF METHODOLOGY PART A AND B

# 3.1 Introduction

The methodology that is developed in chapter 2, is applied here to a case study, in order to define in a real case the opportunities regarding the automated vehicles. More specifically, this chapter elaborates on PART A and B of the methodology, while PART C is extensively presented in chapter 4.

As already mentioned in the beginning of the report, the study case that is chosen for the purposes of this project is the province of Utrecht. This chapter is elaborating on four main points: a) the provision of general information regarding the chosen study case area, b) the presentation of the OmniTRANS model of the province of Utrecht that is used here with its general characteristics, c) the application of Parts A and B of the methodology, namely the identification/design process and the determination of the highest potential train station-zones/routes combinations/cases and d) the model setup of both cases into the OmniTRANS model.

# 3.2 General Information for the Province of Utrecht

The province of Utrecht is considered to be the heart of the Netherlands, since it is located in the middle of the country (Figure 3.1). The province of Utrecht has a population of approximately 1,253,672 people (Wikipedia, 2015), ranking at the 5<sup>th</sup> place of the highest populated provinces in the Netherlands.



Figure 3.1: Province of Utrecht (Source: Google Maps (Google, Province of Utrecht, 2015))

Methodology for assessing the potential of using automated vehicles as an access/egress mode for train trips in a regional setting-An application to the province of Utrecht Moreover, the most important Dutch railway lines meet in Utrecht, giving prominence to the Utrecht's central station as the busiest station in the Netherlands, with approximately 114.000 people arriving or departing every day. Besides the Utrecht central station, there are 27 more train stations currently operating (Figure 3.2), spread over the province of Utrecht. The attraction of so many travellers relies on two points (besides the connectivity in terms of train lines); firstly the existence of the university of Utrecht, one of the biggest universities in the Netherlands, and secondly on the fact that the province lies on the Amsterdam-Rhine Canal, a connection between the respective regions that are considered as one of the largest industrial areas in the world. These facts have allied in order for the province of Utrecht to become one of the busiest provinces in the Netherlands, with not only work-related travellers, but also a lot of students.



Figure 3.2: Train stations of the province of Utrecht (Source: (NS, 2015))

The Province of Utrecht (2010) is presenting in their survey the train stations of the Utrecht province that host more than 5.000 travellers (access, egress or transfer passengers) per day (Figure 3.3), leading to 13 train stations in total in the province that exceed this number of passengers. In this figure, "alleen trein" are the 13 train stations examined, while "in, -uit en overstappers" are the access, egress and transfer passengers. The same survey provides also numerical predictions until 2030, regarding the access and egress trips per mode for train trips in the province of Utrecht (Figure 3.4), revealing high volumes for regional transport modes (such as buses) and followed by also high bicycle volumes (where: "In- en uitstappers trein OVT"=Access and egress train users, "Autoverkeer van/nach stationsgebied"=Car users that access/egress the train stations, "Regionaal OV van/nach stationsgebied"=Regional public transport users that access/egress the train station and "Ter vergelijking: autoverkeer NL"=By comparison: car users in the Netherlands).



Figure 3.3: Train stations of the Utrecht province with more than 5.000 travellers per day (Source: Province of Utrecht, (2010))



Figure 3.4: Predictions for the access/egress trips per mode for train trips in the province of Utrecht (Source: Province of Utrecht, (2010))

# 3.3 The OmniTRANS Model: Province of Utrecht

This chapter aims to provide more insight regarding the model of OmniTRANS that is used for the purposes of the project, and more specifically information about the model of the province of Utrecht. The most important characteristics of the model, as well as further explanation on their values and respective function, where necessary, are in detail presented in Table 3-1.

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Table 3-1: Characteristics of the OmniTRANS model of the province of Utrecht

	Model of The Province of Utrecht
Characteristics	Values/Functions
Travel Choice Model	Four Step Model: • Trip generation • Trip Distribution • Modal Split • Assignment (Static)
Zonal Data	<ul> <li>4400 Zones/Centroids:</li> <li>Province of Utrecht</li> <li>Important Zones of The Rest of The Netherlands</li> </ul>
Aggregative Model	No passenger type classification besides car ownership
Period of the Data	2010
Trip Purposes	Work, Business, Education, Shopping, Others
Time of Day	Morning Peak (Os), Evening Peak (As), Rest of the Day (Rd-> Further Distinction in Rdd for the time between the peaks in the day and Rdan for the night)
Main Trip Modes	Car, Bicycle, PT (Further of PT into all types of trains, all types of buses and Bussen Milieu)
Access/Egress	Car, Pedestrians, Bicycles
Modes	
Users	<ul> <li>For Car-&gt; Car Available and Car Not Available</li> <li>For PT-&gt; Access/Egress Combinations: Car and Bicycle, Car and Pedestrian, Bicycle and Pedestrian, Pedestrian and Pedestrian, Pedestrian and Bicycle, Bicycle and Bicycle (Nested Logit Model)</li> </ul>
Distribution Function and Modal Split Simultaneously	<ul> <li>Doubly Constrained Gravity Model: <ul> <li>a<sub>i</sub>, b<sub>j</sub> are independent-&gt; technique required to derive them (values when balance is accomplished)</li> <li>For the deterrence function f(c<sub>ij</sub>), OmniTRANS is using log-normal function, top-lognormal and exponential</li> <li>Every mode has its own deterrence function-&gt; evaluation of the relative attractiveness of different mode-destination combinations (calculation of respective probabilities)</li> </ul> </li> <li>Functions: <ul> <li>T<sub>ijm</sub> = a<sub>i</sub> × b<sub>j</sub> × P<sub>i</sub> × A<sub>j</sub> × f<sub>m</sub>(c<sub>ijm</sub>)</li> <li>where:</li> <li>T<sub>ijm</sub> = number of trips from zone i to zone j using mode m</li> <li>a<sub>i</sub>, b<sub>j</sub> = scaling factors</li> <li>P<sub>i</sub> = trip production of zone i</li> <li>A<sub>j</sub> = trip attraction of zone j</li> <li>f<sub>m</sub>(*) = <ul> <li>deterence function describing the incentive of travelling to zone j from zone i by mode m</li> <li>and</li> <li>c<sub>iim</sub> = travel impedance (e, a, distance, travel time) of zone i to zone i using mode m</li> </ul> </li> </ul></li></ul>
Assignment	For Car and PT: Volume Average (Deterministic User Equilibrium)
Function	For Bicycle: All or Nothing
Main Attributes For The Car	Cost (tolls, parking charges etc.), Distance, Travel Time, Parking Costs (Penalties)
Main Attributes For The Bicycle	Cost, Distance, Travel Time
Main Attributes For The PT	Distance, Cost, Travel Time, Waiting Time, Penalties, Fares, Transfers

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	Generalized Cost (simple linear function)
Travel Impedance c <sub>ij</sub>	<b>Function Type:</b> e.g. $GC = \alpha \times D + \beta \times T + \gamma \times C$ where: GC = generalized cost D = distance T = travel time (includes also junction delays, if function modelling is activated) C = optional additional fixed link cost (tolls, parking charges etc.) $\alpha = coefficient for distance applied thoughout the network$ $\beta = coefficient for time applied thoughout the network$ $\gamma = coefficient for the C cost$
Number of Iterations	1

These model characteristics are general, though more detailed description, in combination with the specific Utrecht model, is elaborated in the next parts of this chapter.

# 3.4 PART A and B: Identification/Design Process and Determination of Cases

This part is elaborating on Parts A and B of the methodology. In PART A, the identification/design processes of the train station, zone and route levels of the province of Utrecht are developed, with the application of the respective level criteria, as determined in chapter 2.2. Also, in this part, the sensitivity analysis on the zone level and the validation on both train station and zone level are applied, based on the methodology (chapter 2.2.4). In PART B, the determination of the cases is presented based on the outcomes of Part A. In this project, only two train station-zones-routes cases are determined. Each case has the same number of zones that are potentially applied for the operation of the automated vehicles (4 zones). Moreover, their connection to the train station is based on two scenarios: a) the current bus line based and b) the shortest path based routes. The choice regarding the number of zones is determined already after the completion of the zone level application, because of time limitations regarding the completion of the project that did not allow the investigation of more zone options (in terms of number of zones selected per case). Afterwards, the choice of the route options is determined, which are connecting the 4 zones with the selected train station. The route options preceded the completion of the route design level, due to, again, limitations of time to investigate all potential route options around the train station and the selected 4 zones. For all these reasons, the determination of the zones/routes cases in the case study are applied simultaneously with the outcomes of PART A, as is in detailed described in chapter 3.4.3.

## 3.4.1 Identification level 1: train stations in the province of Utrecht

Following the criteria that are defined in the methodology chapter regarding the train station level (2.2.1), the outcomes of this analysis level are presented in this chapter.

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## Train station identification level-Criterion 1.1

The starting criterion, which requires the determination of the number of trips (access and egress train trips) per train station, is processed, according to equation 1.2. The threshold used for this criterion ( $\alpha_1$ ) is equal to:

$$\alpha_1 = 5.000 \ train \ trips/day$$

The choice of this specific threshold is based on the research of the Province of Utrecht (2010), which used the threshold of 5.000 train trips/day in order to choose between the high and low/medium demand train stations. The application of the first criterion and the respective outcomes for each one of the 28 train stations of the province of Utrecht (rounded) are shown in Table 3-2:

Train Stations	Number of Access Trips	Number of Egress Trips	Train Stations	Number of Access Trips	Number of Egress Trips
Abcoude	1600	1400	Rhenen	3000	2300
Amersfoort	10100	9800	Soest	300	100
Amersfoort Schothorst	13100	11100	Soest Zuid	1700	400
Amersfoort Vathorst	3600	5500	Soestdijk	1000	1000
Baarn	5900	5500	Utrecht Centraal	23000	24900
Bilthoven	3000	3900	Utrecht Overvecht	6500	8500
Breukelen	5000	5400	Utrecht Terwijde	4700	4400
Bunnik	3600	4200	Utrecht Zuilen	3200	2900
Den Dolder	1500	2300	Utrecht Lunetten	2400	3200
Driebergen- Zeist	8000	8000	Veenendaal Centrum	2400	2000
Hollandsche Rading	800	1000	Veenendaal De Klomp	7200	7200
Houten	6500	7300	Veenendaal West	2700	2100
Maarn	3500	2700	Vleuten	4300	4100
Maarssen	6100	6100	Woerden	12700	12300

 Table 3-2: Results of criterion 1.1 of the train station identification level

In Table 3-2 the colours represent the ranking of each station, compared to the threshold of 5.000 train trips/day. So, the biggest train stations of the area, namely Amersfoort, Amersfoort Schothorst, Utrecht Centraal and Woerden scored very high compared to this threshold, and so, excluded from the following identification process. The pink coloured train stations depict the train stations that have access and egress train volumes lower than the  $\alpha_1$ . The orange coloured train stations are the ones that have train trips above the value of  $\alpha_1$ , but very close to it, compared to the large train station volumes, and therefore, investigated for criterion 1.2.

## Train station identification level-Criterion 1.2

The next criterion involves the determination of the access/egress trips performed by each mode from the train stations. The modes available from the OmniTRANS model are the car, bicycle, bus and pedestrians. Important to mention that access and egress trips are not considered here as last mile trips, that is why the bus is also included in this criterion. The equations related to this criterion (1.2, 1.3 and 1.4) are applied to each train station and the respective thresholds per criterion are:

 $\alpha_2 \ge 300 \ car \ trips/day$  $\alpha_3 \le 300 \ bus \ trips/day$  $\alpha_4 \le 1000 \ bicycle \ trips/day$ 

The choice of these specific thresholds derived from the observation of the data of the OmniTRANS model for the province of Utrecht and the determination of an average value, based on all train stations investigated. The application of all 3 equations of criterion 1.2 and the respective outcomes (rounded) are presented in Table 3-3:

Number of Access/Egress Trips Per Mode								
Train Stations	Bicy	cles	Pedes	trians	Ca	ar	Βι	IS
	Access	Egress	Access	Egress	Access	Egress	Access	Egress
Abcoude	450	500	500	400	600	600	0	0
Amersfoort Vathorst	1500	2500	1600	1000	500	2100	0	0
Baarn	2800	3200	1600	800	1600	1600	200	0
Bilthoven	1500	1900	1400	700	100	1200	0	100
Breukelen	1900	2400	800	300	2300	2700	1000	1000
Bunnik	2300	3400	1100	700	100	100	600	300
Den Dolder	600	1000	700	600	300	600	0	0
Driebergen-Zeist	4700	5700	1600	500	1800	1800	1700	1500
Hollandsche Rading	300	400	300	200	200	300	0	0
Houten	2200	3400	3100	2300	1200	1600	800	800
Maarn	500	600	700	500	2300	1600	300	400
Maarssen	3700	4800	2200	1100	200	300	100	0
Rhenen	800	900	600	300	1600	1200	2500	2000
Soest	100	0	100	0	0	0	0	0
Soest Zuid	900	100	800	300	0	0	0	0
Soestdijk	400	200	600	700	0	0	0	100
Utrecht Overvecht	3900	6500	2500	1700	100	300	400	100
Utrecht Terwijde	2800	3200	1700	900	100	200	0	0
Utrecht Zuilen	1800	1900	1300	900	0	0	0	0
Utrecht Lunetten	800	1500	1200	1100	400	500	400	700
Veenendaal Centrum	900	1100	1200	600	400	300	300	200
Veenendaal De Klomp	4200	5000	1500	800	1500	1400	1400	1300
Veenendaal West	600	800	1500	800	600	500	0	0
Vleuten	2400	3000	1800	1000	100	100	100	0

Table 3-3: Results of criterion 1.2 of the train station identification level

Methodology for assessing the potential of using automated vehicles as an access/egress mode for train trips in a regional setting-An application to the province of Utrecht The main focus, as explained in chapter 2.2.1, is to identify stations with relatively high car volumes and low bus/bicycle usage, compared to the car trips. The red coloured train stations (8 in total) are the ones that meet the requirements for being the highest potential train station according to criterion 1.2. Finally, the train stations without a colour are the ones that do not fulfil one or more of the 3 equations of criterion 1.2 (either very low car usage, or very high bus/bicycle volumes).

## Train station identification level-Criterion 1.3

Criterion 1.3, which selects the highest potential train station based on zone-related characteristics, consists of 5 constraints (all zone-related). All 5 constraints are applied simultaneously to all train stations derived after the application of criterion 1.2. The outcomes of each constraint are elaborated in the following parts.

## Criterion 1.3-Constraint 1.1

According to constraint 1.1, as developed from the methodology (chapter 2.2.1), the total number of trips, car volumes, number of work/business related trips by car and PT volumes are examined for the zones that are associated to each train station, given a specific accessibility radius. The accessibility radius in this project is defined by taking into account that the focus is on access/egress trips and not on main trips. So, for train trips in the Netherlands, the travel distance from/to each train station for an access/egress trip is defined in the research of Krygsman, Dijst, & Arentze (2004) to be approximately 3-4 km. Based on this accessibility measure for access/egress trips, the radius around each of the 8 train stations that are derived after the application of criterion 1.2, is selected to be 3-4 km. For better overview of the location of the zones around each of the 8 train stations within the accessibility radius, Appendix B is used with respective figures.

After determining the zones that are associated to each of the 8 train stations, constraint 1.1 is applied to each zone, using the equations 1.7, 1.8, 1.9 and 1.10 (chapter 2.2.1), based on the thresholds defined for each equation below (the choice of these specific thresholds derived from the observation of the data of the OmniTRANS model for the province of Utrecht, namely the average values for all zones examined):

 $\alpha_5 \ge 7000 \text{ total trips/day}$  $\alpha_6 \ge 2000 \text{ car trips/day}$ 

 $\alpha_7 \ge 800 \text{ car trips/day for work and business purposes}$ 

 $\alpha_8 \leq 1000 \ bus \ trips/day$ 

Based on the outcomes of applying each equation to all zones of the 8 chosen train stations, the higher potential zones are derived. These zones for each train station are presented in Table 3-4.

Table 3-4: Results of constraint 1.1 of criterion 1.3 of the train station identification level

Train Stations	Potential Zones	Train Stations	Potential Zones
Station Abcoude	2043	Station Veenendaal Centrum	2303
	2044		2298
	2045		2301
Station Bilthoven	1498		2307
Station Den Dolder	1606		2308
Station Hollandsche Rading			2315
Station Maarn	2254		2296
	2256		2297
Station Utrecht Lunetten	6		2316
	11		2310
	17	Station Veenendaal West	2303
			2307
			2308
			2315

The resolution of constraint 1.1 has defined the train stations that are complying with constraint 1.3 and are highlighted with red colour in Table 3-4. So, train stations Abcoude, Veenendaal Centrum and Veenendaal West are further examined for constraint 1.2.

## Criterion 1.3-Constraint 1.2

Constraint 1.2 is trying to identify the zones of the train stations that derived from constraint 1.1 that are associated to the respective train station and not to another train station, applying equations 1.11 and 1.12 (chapter 2.2.1). The outcome of the application of constraint 1.2 is presented in Table 3-5.

Table 3-5: Results of constraint 1.2 of criterion 1.3 of the train station identification level

Train Stations	Potential Zones
Station Abcoude	2043
	2044
	2045
Station Veenendaal Centrum	2303
	2298
	2301
	2307
	2308
	2310
	2296
	2297
Station Veenendaal West	2315

## Criterion 1.3-Constraint 1.3

Constraint 1.3 is identifying the potential zones that are located further than walking/cycling distance (more than 1 km travel distance) from its associated train station. The zones per

train station that derived from applying equation 1.13 of constraint 1.3 (chapter 2.2.1) are presented in Table 3-6:

Train Stations	Potential Zones
Station Abcoude	2043
	2044
	2045
Station Veenendaal Centrum	2303
	2298
	2301
	2307
	2308
	2310

Table 3-6: Results of constraint 1.3 of criterion 1.3 of the train station identification level

## Criterion 1.3-Constraint 1.4

As can be observed, after the implementation of constraint 1.3, Veenendaal West is no longer an "attractive" option for the automated vehicles, whereas the number of zones for the rest of the stations has significantly diminished. Constraint 1.4, regarding the bus service level (total average on-board passengers) for all bus lines serving each candidate train station with their associated zones, is applied to each of the two train stations that derived from constraint 1.3. The equation 1.14 for this constraint (chapter 2.2.1) is using as threshold the value (only for morning peak):

## $\alpha_9 = 150$ Total on – board passengers all bus lines included/morning period

The choice of this specific threshold derived from the observation of the data of the OmniTRANS model for the province of Utrecht, namely the average values for all associated zones of each train station examined. The general outcomes for each station are shown in Table 3-7. It is worth mentioning that the time period selected for the purposes of this constraint is the morning peak, a period of the day with very high frequencies and on-board passengers for bus lines, compared to the rest of the day, so representative of the maximum possible bus service level of the day.

Train Stations	Bus Lines	Frequencies (In Morning Peak) (vehicles/hour)	Average On-Board Passengers For Morning Peak (Per Direction Per Vehicle)	Total On-Board Passengers In Morning Peak	Total Average On- Board Passengers (For All Bus Lines) In Morning Peak (Per Train Station)
Abcoude	120	2	30	120	
	126	2	25	100	110
Veenendaal Centrum	80	2	40	160	
	81	2	40	160	
	83	2	40	160	
	87	2	15	60	135

Table 3-7: Results of constraint 1.4 of criterion 1.3 of the train station identification level

Methodology for assessing the potential of using automated vehicles as an access/egress mode for train trips in a regional setting-An application to the province of Utrecht | According to the above table, both train stations have similar total average on-board passengers for all bus lines serving the train station and the associated zones (110 for Abcoude and 135 for Veenendaal Centrum). Although there is a difference between those values, it is also important to take into account the number of zones served by Veenendaal Centrum within the chosen accessibility radius (6 in total) compared to Abcoude train station (3 in total). This means that, while Veenendaal Centrum is having slightly higher number of average on-board passengers than Abcoude for its bus lines, nevertheless, when taking into account the number of zones served, analogically Veenendaal Centrum is serving lower number of people than Abcoude. That is why the final constraint of the train station identification level is applied, in order to finally define the highest potential train station among Abcoude and Veenendaal Centrum.

#### Criterion 1.3-Constraint 1.5

The last constraint of criterion 1.3 involves the choice of the highest potential train station, based on the maximum number of potential zones that are associated to each train station. As is observed already from constraint 1.4, Veenendaal Centrum has more potential zones than Abcoude. So, applying equation 1.15 of constraint 1.5 (chapter 2.2.1), the mathematical value used is:

$$Z_{i,j} = Z_{max} = 6$$
 zones

Based on the outcomes of applying this constraint, the final choice is the train station of Veenendaal Centrum, which has the largest number of potential zones, compared to Abcoude (Figure 3.5). This train station is located on the eastern part of the province of Utrecht, close to Veenendaal West and Veenendaal De Klomp train stations.



Figure 3.5: Veenendaal Centrum train station with the potential zones in OmniTRANS environment

Methodology for assessing the potential of using automated vehicles as an access/egress mode for train trips in a regional setting-An application to the province of Utrecht

## 3.4.2 Identification level 2: zones associated to Veenendaal Centrum

After the highest potential train station has been selected (Veenendaal Centrum) in chapter 3.4.1, the next identification level is the zone level. The purpose of this level is to determine the highest potential zones of Veenendaal Centrum that resulted from the application of all constraints of criterion 1.3, by ranking them, based on the criteria defined in chapter 2.2.2 (equation 2.16).

In this level, every criterion is applied to each zone simultaneously. The explanation and measurements for each zone level criterion are the following:

- > **Zone identification level-Criterion 2.1:** # of total trip generation per zone
- Zone identification level-Criterion 2.2: % of bicycles, compared to the total number of trips (average of production and attraction trips) per zone
- Zone identification level-Criterion 2.3: % of bicycle trips, compared to the total number of trips, for work and business purposes (average of production and attraction trips) per zone
- Zone identification level-Criterion 2.4: % of bicycles, compared to the number of trips performed by Car+PT (average of production and attraction trips) per zone
- Zone identification level-Criterion 2.5: % of bicycles, compared to the number of trips performed by Car+PT, for work and business purposes (average of production and attraction trips) per zone

The application of equations 2.17, 2.18, 2.19, 2.20 and 2.21 have, for this project, thresholds equal to:

 $\alpha_{10} \ge 9000 \ trips/day$  $\alpha_{11} \le 60 \ \%$  $\alpha_{12} \le 10 \ \%$  $\alpha_{13} \le 1,8$  $\alpha_{14} \le 0,7$ 

The choice of these specific thresholds derived from the observation of the data of the OmniTRANS model for the province of Utrecht, and more specifically, from the average values of all zones examined. So, after investigating all zones with all the respective criteria, the outcomes (rounded) per criterion are shown in the following tables (Table 3-8-Table 3-12).

Table 3-8: Results of criterion 2.1 of the zones identification level

Potential Zones	Total trips (both attraction and production)
2301	43000
2303	14000
2307	21000
2308	18000
2298	26000
2310	29000

Table 3-9: Results of criterion 2.2 of the zones identification level

Potential Zones	Percentage of bicycles out of the total number of trips
2301	47
2303	50
2307	44
2308	52
2298	44
2310	48

Table 3-10: Results of criterion 2.3 of the zones identification level

Potential Zones	Percentage of bicycle trips for work/business purposes (average of production and attraction trips)
2301	10
2303	9
2307	8
2308	7
2298	9
2310	8

Table 3-11: Results of criterion 2.4 of the zones identification level

Potential Zones	Percentage of bicycles compared to Car+PT trips (average of production and attraction trips)
2301	81
2303	102
2307	82
2308	174
2298	80
2310	109

Table 3-12: Results of criterion 2.5 of the zones identification level

Potential Zones	Percentage of bicycles compared to Car+PT trips for working/business purposes (average of production and attraction trips)
2301	61
2303	66
2307	43
2308	46
2298	55
2310	47

Taking into account the values of the 6 zones for each individual criterion, a need has risen to place these values into a concrete and general ranking system, based on all 5 criteria. For the purposes of this request, a score card is created, in which each zone is ranked for each of the 5 criteria according to their values derived from Table 3-8-Table 3-12. However, since the criteria have different measurements and different values, the approach of dealing with these differences, at first, is through the weighted difference method, with the general mathematical formulation:

$$S_{Zone} = (X - X_{min}) / (X_{max} - X_{min})$$

where:

Table 3-13: Evaluation of the zones

 $S_{Centroid}$  = The scaling value per zone investigated within the same criterion X = The value of the zone investigated within the same criterion  $X_{min}$  = The value of the zone with the minimum value within the same criterion  $X_{max}$  = The value of the zone with the maximum value within the same criterion

With this formula, the lowest value is translated as "worst scoring zone", whereas the "best scoring zone" is the one with the highest value. However, this scoring system is representative only for criterion 2.1. For the last 4 criteria, though, the opposite should be applied: the higher the values for each criterion, the worst they should score. In order to correct this point, each of the values for the last 4 criteria is subtracted from 1. The final outcomes of this subtraction and the total score for all criteria per zone are illustrated in Table 3-13.

		Potential Zonos							
Criteria	Potential Zones								
	2301	2303	2307	2308	2298	2310			
Criterion 2.1	1	0	0.22	0.11	0.39	0.51			
Criterion 2.2	0.62	0.25	1	0	1	0.5			
Criterion 2.3	0	1	0.5	0.75	0.25	0.5			
Criterion 2.4	0.99	0.77	0.98	0	1	0.69			
Criterion 2.5	0.26	0	1	0.87	0.48	0.87			
Total	2.87	2.02	3.7	1.73	3.12	3.07			

The conclusion, after the evaluation, is that zone 2307 is scoring the highest among all the rest zones, followed by zones 2298, 2310 and 2301. Zones 2303 and 2308 score the lowest, compared to the rest, with a relatively high difference. This difference clearly provides an

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insight regarding the final choice of the zones that are further used for the final route design level in chapter 3.4.4, namely zones 2301, 2307, 2298 and 2310.

## Sensitivity analysis

Although the above evaluation method clearly showed that zones 2298, 2301, 2307 and 2310 are the highest potential ones for applying them to the final design route level, it is important to assure that this choice is robust. In order to accomplish this, a sensitivity analysis is performed, as defined in chapter 2.2.4. The method used for the sensitivity analysis is a simple score card method, with the values determined in Table 3-13 as input for the sensitivity analysis, but with two different weighting systems for each of the criteria.

The first weighting system is using a weight of 30% for criterion 2.1 and equal weights of 17,5% for the rest criteria, whereas the second system provides a weight of 40% for criterion 2.1, and equal weights of 15% for the remaining criteria. The reason for differentiating only the first criterion, in terms of weights, is dual: a) criterion 2.1 is important since it identifies the number of total trips, so it captures the total potential demand for the automated vehicles b) the rest of the criteria are all referring to the same mode, namely the bicycle, so it is assumed in this analysis that their influence to the final choice is relatively the same to all zones. The outcomes of the score card for the two weighting systems are shown in Table 3-14 and Table 3-15 respectively.

Criteria	Potential Zones					Moighto (%)	
	2301	2303	2307	2308	2298	2310	weights (%)
Criterion 2.1	0.3	0	0.07	0.03	0.01	0.02	30
Criterion 2.2	0.11	0.04	0.18	0	0.18	0.09	17.5
Criterion 2.3	0	0.18	0.09	0.13	0.04	0.09	17.5
Criterion 2.4	0.17	0.13	0.17	0	0.18	0.12	17.5
Criterion 2.5	0.04	0	0.18	0.15	0.08	0.15	17.5
Total	0.62	0.35	0.69	0.31	0.49	0.47	

Table 3-14: Sensitivity	analysis with t	he first weighting sv	stem (30% for criterior	12.1)
rable of 2 in belibiting	analysis men	ine more weighting by		· -· - /

Table 3-15: Sensitivity	analysis with the second	weighting system	(40% for criterion 2.1)
			(

Criteria	Potential Zones					Moighto (%)	
	2301	2303	2307	2308	2298	2310	weights (%)
Criterion 2.1	0.4	0	0.09	0.04	0.16	0.20	40
Criterion 2.2	0.09	0.04	0.15	0	0.15	0.08	15
Criterion 2.3	0	0.15	0.08	0.11	0.04	0.08	15
Criterion 2.4	0.15	0.12	0.15	0	0.15	0.10	15
Criterion 2.5	0.04	0	0.15	0.13	0.08	0.13	15
Total	0.68	0.31	0.62	0.28	0.58	0.59	

The outcomes of Table 3-14 show that zones 2298, 2301, 2307 and 2310 are scoring higher than zones 2303 and 2308, the same outcomes as in Table 3-13, however, zone 2301 is scoring second after zone 2307, followed by zones 2310 and 2298. This is justified by the fact that the higher weight for the first criterion is upgrading the total score of zone 2301, which has the highest number of total trips, compared to the other 5 zones. And this is more

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depicted in Table 3-15, where the weight for the first criterion increases more, and so, zone 2301 becomes the leading option among all zones, followed by zones 2298, 2307 and 2310. Again, zones 2303 and 2308 are in both weighting systems in the last two ranking positions.

In total, this sensitivity analysis showed that the evaluation method used in Table 3-13 is quite robust, in terms of the final choice of the zones that are used for the final route design level. The outcomes of Table 3-14 and Table 3-15, although slightly different regarding the first chosen zone, still are promoting the same zones as highly scored options for the route design level, namely zones 2301, 2307, 2298 and 2310.

## Validation

A crucial step, before elaborating on the design route level, is the validation process, as explained in chapter 2.2.4. The validation is handled as followed:

- All 24 train stations (besides train stations Amersfoort, Amersfoort Schothorst, Utrecht Centraal and Woerden, which are very large train stations, as explained in chapter 3.4.1) are included in the validation process.
- Zones within the accessibility radius of 4 km around each of the 24 train station are chosen.
- From all these zones, only the ones that are complying with the three criteria 1.3, 1.4 and 1.5 of the train station level (see chapter 3.4.1), are chosen.
- > Evaluation of these zones based on the criteria of the zones identification level.

With this approach, all zones of every train station that comply with the basic criteria 1.3, 1.4 and 1.5 of the train station identification level are evaluated for all the zones identification level criteria. The reason for using only these 3 criteria as prerequisite for choosing the zones that are evaluated further, is to:

- 1. Define certain basic rules regarding the choice of zones that are validated.
- 2. Not pre-restrain the choice of zones with more criteria, in order to leave room for identifying all possible options.

After the evaluation of the zones with the respective zone level criteria, the highest potential zones, and so, their respective train stations, reveal. The validation process aims to prove that the zones and train stations that are chosen as highest potential are the same, either starting from the train station identification level or from the zones identification level.

Table 3-16 shows the zones per train station that accomplish the basic train station level criteria 1.3, 1.4 and 1.5:
#### Table 3-16: Zones per train station used for validation

Train Station	Associated Zone	Train Station	Associated Zone
Abcoude	2045	Utrecht Zuilen	135
Amersfoort Vathorst	2181	Utrecht Zuilen	164
Amersfoort Vathorst	2186	Utrecht Zuilen	169
Baarn	2082	Utrecht Zuilen	170
Bilthoven	1498	Utrecht Zuilen	172
Bunnik	1574	Veenendaal West	2292
Den Dolder	1606	Veenendaal De Klomp	2293
Houten	958	Veenendaal De Klomp	2294
Houten	981	Veenendaal De Klomp	2295
Rhenen	2324	Veenendaal Centrum	2301
Rhenen	2332	Veenendaal Centrum	2303
Rhenen	2334	Veenendaal Centrum	2307
Rhenen	2336	Veenendaal Centrum	2308
Soest Zuid	2112	Veenendaal Centrum	2298
Soestdijk	2107	Veenendaal Centrum	2310

For these zones, the same zone criteria and evaluation method is used for the validation process, as in the beginning of chapter 3.4.2. Also, in order to check the robustness of the outcomes of the evaluation, the same sensitivity analysis is performed, as in chapter 3.4.2. The outcomes of this evaluation and sensitivity analysis for all the zones are illustrated in Table 3-17.

#### Table 3-17: Validation process

Train Station	Zone	Criterion 2.1	Criterion 2.2	Criterion 2.3	Criterion 2.4	Criterion 2.5	Total Score 1	Total Score 2 (Weight 30%)	Total Score 3 (Weight 40%)
Abcoude	2045	0.13	0.53	0.94	0.80	0.84	3.23	0.58	0.52
Amersfoort Vathorst	2181	0.22	0.49	1.00	0.78	0.81	3.29	0.60	0.55
Amersfoort Vathorst	2186	0.37	0.37	0.92	0.72	0.64	3.02	0.57	0.55
Baarn	2082	0.46	0.56	0.85	0.82	0.69	3.39	0.65	0.62
Bilthoven	1498	-0.05	0.78	0.28	0.92	0.75	2.68	0.46	0.39
Bunnik	1574	-0.14	1.00	0.56	1.00	0.98	3.40	0.58	0.48
Den Dolder	1606	-0.08	1.01	0.65	1.00	1.00	3.58	0.62	0.52
Houten	958	-0.12	0.30	0.74	0.67	0.38	1.98	0.33	0.27
Houten	981	-0.11	0.27	0.79	0.66	0.48	2.09	0.35	0.29
Rhenen	2324	-0.05	0.42	0.99	0.74	0.78	2.89	0.50	0.42
Rhenen	2332	0.00	0.32	0.91	0.69	0.66	2.57	0.45	0.39
Rhenen	2334	-0.11	0.18	0.78	0.59	0.53	1.97	0.33	0.27
Rhenen	2336	0.04	0.26	0.93	0.65	0.60	2.47	0.44	0.38
Soest Zuid	2112	0.10	0.30	0.80	0.68	0.37	2.24	0.40	0.36
Soestdijk	2107	-0.01	0.49	0.89	0.78	0.60	2.75	0.48	0.41
Utrecht Zuilen	135	-0.07	0.47	0.67	0.77	0.35	2.18	0.37	0.31
Utrecht Zuilen	164	-0.13	0.38	0.71	0.72	0.32	2.00	0.33	0.27
Utrecht Zuilen	169	0.00	0.32	0.62	0.69	0.33	1.95	0.34	0.29
Utrecht Zuilen	170	-0.10	0.36	0.69	0.71	0.31	1.96	0.33	0.27
Utrecht Zuilen	172	-0.08	0.31	0.69	0.68	0.23	1.84	0.31	0.26
Veenendaal West	2292	0.13	0.69	0.00	0.88	0.56	2.26	0.41	0.37
Veenendaal De Klomp	2293	0.00	0.64	0.04	0.86	0.52	2.06	0.36	0.31
Veenendaal De Klomp	2294	-0.13	0.64	0.50	0.85	0.63	2.49	0.42	0.34
Veenendaal De Klomp	2295	0.01	0.63	0.43	0.85	0.60	2.52	0.44	0.38
Veenendaal Centrum	2301	1.00	0.18	0.68	0.65	0.12	2.63	0.59	0.64
Veenendaal Centrum	2303	0.17	0.07	0.75	0.51	0.00	1.50	0.28	0.27
Veenendaal Centrum	2307	0.36	0.29	0.83	0.65	0.53	2.65	0.51	0.49
Veenendaal Centrum	2308	0.26	0.00	0.90	0.00	0.46	1.62	0.32	0.31
Veenendaal Centrum	2298	0.50	0.29	0.75	0.66	0.27	2.46	0.49	0.49
Veenendaal Centrum	2310	0.59	0.14	0.83	0.46	0.44	2.45	0.50	0.52

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The Total Score 1 column in Table 3-17 represents the outcomes of the weighted difference method, as applied in Table 3-13, while the last two columns are the outcomes of the sensitivity analysis per zone with respective weights 30% and 40%. According to Table 3-17, some zones in column Total Score 1 are scoring higher than the highest potential zones around Veenendaal Centrum (2298, 2301, 2307 and 2310). Some of these zones are scoring higher from the 4 highest potential zones of Veenendaal Centrum even after the sensitivity analysis (last two columns of Table 3-17). However, in total, the 4 zones of Veenendaal Centrum, and so, the respective train station of Veenendaal Centrum, is scoring very high, confirming that Veenendaal Centrum is a justified choice as highest potential train station, as well as its respective zones (2298, 2301, 2307 and 2310). Nevertheless, the fact that other zones (around Den Dolder, Abcoude, Veenendaal De Klomp, Amersfoort Vathorst or Bunnik) are scoring higher in the validation than the ones of Veenendaal Centrum, leaves room for further investigation of these zones as potential application points for the automated vehicles. In conclusion, the methodology is considered as relatively valid, since the same choices of train station and zones are determined both starting from the train station level and continuing to the zone level or the other way around.

# 3.4.3 Determination of train station-zones-routes combinations/cases

The determination of different train station-zones-routes cases, as discussed in chapter 2.3, and more specifically the selection of the zones and routes that are determining the train station-zones-routes cases, is performed here, instead of after the completion of the route design level. The purpose of this choice is dual:

- 1. Due to time limitations for accomplishing this project, in combination with the high running time of each case by the model (over 1 day), not all cases could be examined, based on the different number of zones, as discussed in chapter 2.3.
- 2. In the route level, all potential routes around Veenendaal Centrum should be examined, in order to exclude the routes/links that are not appropriate choices, as defined in chapter (2.2.3). This process, however, is time consuming, and thus, not possible for the time limitations of this project.

Based on the above points, the number of zones included in the route level design is determined here, as well as the respective route scenarios that are created here and would connect Veenendaal Centrum with the chosen zones. More detailed explanation for these selections is presented in the following parts.

# Zone selection

The zones that are chosen for connecting Veenendaal Centrum with automated vehicles are zones 2298, 2301, 2307 and 2310. The outcomes of Table 3-13, as well as the outcomes of the sensitivity and validation process, showed that these 4 zones are the highest potential zones among all 6 associated to Veenendaal Centrum. For this reason, all 4 are chosen for the final route design level, where the routes for connecting them with Veenendaal Centrum are determined. Although the determination of the number of zones per case is a process that follows after the execution of the route design level, nevertheless, in this project, the

zone selection is preceding. The reason is to simplify the route design process and have concrete view over the number of zones the automated vehicles would operate, in order to save time from the route selection process. With this approach, also route scenarios are predefined here, so that not all possible set of routes would be examined between Veenendaal Centrum and the 4 selected zones.

# Route selection

In chapter 2.2.3, besides the number of zones that would define different train stationzones-routes cases, also the different aspects of routes are involved into the determination of cases. These aspects could be the operation of the automated vehicles on current bus line network or the use of other routes, for instance the shortest path route. Also, other aspects are the operation of the automated vehicles inside city centres or not. All these, and many more options, could provide a large set of potential routes, which could all be examined in different train station-zones-routes cases, combined with the choice upon the number of zones that the automated vehicles serve per case. The route selection, based on chapter 2.3, should be determined after the execution of the route design level, so that the unsuitable routes/links are excluded, before elaborating on the different route options.

However, due to time limitations of this project, the route selection is pre-defined based on two route scenarios. These routes are further evaluated in the route design level for their suitability, according to criteria 3.1-3.5 of the route design level:

- Current bus line route scenario: In this route scenario, the route that is selected for each zone tries to incorporate the routes of the current bus lines that are serving the zones selected. Exception: In case of non-availability of bus lines around certain zones, the route includes links that have the highest possible road speeds (connected to the road types of the available network).
- Shortest path route scenario: In this route scenario, the automated vehicles follow links that are part of the shortest routes that connect the zones with each other and with the train station. Exception: links that are not used by all types of vehicles (dependent on the road type). In this case, links that have the highest possible road speeds (connected to the road types) are selected.

The difference between the two scenarios is that the first is aiming for a route that is currently used by bus lines (with the respective bus stops) and at the same time it tries to comply with the criteria of chapter 2.2.3, whereas the second is aiming for the shortest possible path between each zone and the chosen train station, regardless of the current bus lines' routes (and existing bus stops), and is, as well, aiming to comply with the same criteria. So, the difference relies on the different requirement each of the route scenario has, rather than on the criteria themselves. Both route scenarios are providing one individual route that connect the 4 selected zones with Veenendaal Centrum (Figure 3.6) and are both evaluated based on the route design level criteria (chapter 3.4.4).



Figure 3.6: a) Left: Case 1: Current bus line based b) Case 2: Shortest path based

### 3.4.4 Design level 3: routes for Veenendaal Centrum and selected zones

In order to assure that the 2 routes determined in the route scenarios above (current bus line based and shortest path based) that connect Veenendaal Centrum and the 4 chosen zones (2298, 2301, 2307 and 2310) are valid, the route design criteria (chapter 2.2.3) are applied to both routes. Criterion 3.1 requests that each route is connecting the maximum number of selected zones. Criterion 3.2 determines the travel distance limit per direction for each route, while criterion 3.3 is constraining the route choices to only the ones that have congestion levels per link under certain levels. Finally, criterion 3.4 is focusing on routes with links that allow certain operational speed limits, whereas criterion 3.5 is assuring that the chosen links per route are allowing the movement of motorised vehicles. In respect to these criteria, equations 3.23-3.30 are executed for both routes derived from the route scenarios above. The thresholds required for equations 3.26 and 3.28, which reflect the congestion level and the operational speed level respectively, are presented below:

 $\alpha_{15} \le 0.8$ 

$$\alpha_{16} \ge 40 \ km/h$$

For the congestion level threshold, the choice is based on the outcomes of the model, regarding congested links/routes. As for the operational speed threshold, this choice is justified by the assumption that the operational speed of the bus (and thus of the automated vehicle) is lower than the maximum operational speed offered per link, so in

order to assure high operational speeds for the automated vehicles, a minimum operational boundary of 40 km/h in each link is used. After the execution of the route level criteria to both routes defined per route scenario (Figure 3.6), these routes are both complying with the criteria, so these routes are finally chosen for the final train station-zones-routes cases:

- Case 1: Current Bus Line Based. In this case (Figure 3.6-Left), the automated vehicles connect the train station of Veenendaal Centrum with the associated zones 2298, 2301, 2307 and 2310, with the route that follows the current bus lines (bus stops), as defined in the first route scenario.
- Case 2: Shortest Path Based. In this case (Figure 3.6-Right), the automated vehicles connect the train station of Veenendaal Centrum with the associated zones 2298, 2301, 2307 and 2310, with the route that is using the shortest travel distance among all zones selected and the train station, as defined in the second route scenario.

However, it is important to highlight that there certain minor adjustments are made, so that the operation of the automated vehicles would be smooth. This means that in both route selections, almost all links connecting the zones with the train station had a maximum bus speed of 40 km/h and above. However, in certain links (see  $\Sigma \phi \dot{\alpha} \lambda \mu \alpha$ ! To  $\alpha \rho \chi \epsilon i \sigma \pi \rho \epsilon i \lambda \epsilon u \sigma \eta \epsilon$ ,  $\alpha \nu \alpha \phi \rho \rho \dot{\alpha} \varsigma \delta \epsilon \nu \beta \rho \epsilon \theta \eta \kappa \epsilon$ . the links within the green circle close to zone 2310), have a maximum bus speed of 20 km/h. Since the links with this problem are exceptions, it is accepted, for the purposes of this project, that they could be chosen as part of the routes. In order to assure that these links are appropriate from an infrastructure point of view (width of the road), the use of google maps (Google Maps, 2015) is requested and view each road link. The outcome of this investigation is that these links are having adequate road length to support the operation of the automated vehicles. In summary, although these links are "violating" the last two criteria of the route design level (criteria 3.4 and 3.5), nevertheless their length is very short and is assumed that they are not affecting the total travel time of each route.

# 3.5 Determination of OmniTRANS Model Setup for the Province Of Utrecht

This last part of chapter 3 is presenting the main input data for the OmniTRANS model of Utrecht, based on the outcomes of Parts A and B (chapter 3.4), in order to introduce the automated vehicles into the existing network. This part involves the elaboration of many important aspects. Firstly, the Value of Time (VoT) of the automated vehicles is defined. Furthermore, the pure modelling of the new mode, as well as the determination of the generalized cost functions is presented. Moreover, the vehicle specifications for this case study, the AV stops per case and the model parameters necessary for the introduction of the automated vehicles are elaborated. Finally the number of vehicles required for the smooth operation of the new system, in relation to the current train frequencies, is determined. All the above are in detail described in the following parts.

# **3.5.1** VoT of the automated vehicles

As already explained in chapter 3.4.4, the outcome of Parts A and B provides 2 different cases that connect Veenendaal Centrum with zones 2298, 2301, 2307 and 2310, depending on the type of the route itself (following the current bus line route or based on the shortest path application). These 2 different cases are applied in the model in order to define the potential demand and general network results regarding the automated vehicles. Each of these cases is chosen to have the same operational and model characteristics (VoT, generalized cost function variables, coefficients, speed, frequencies, waiting times etc.), with only difference the number of bus stops used per case, which is further explained in chapter 0.

The VoT for the automated vehicles is chose to be equal to the VoT for the BTM, currently used by the model of OmniTRANS. Though, there are certain points that request special attention:

- The VoT in the model is defined only for the main modes (car, bicycle and PT, whereas for the PT, a separation is being made between train and BTM).
- The VoT per main mode is defined per trip purpose (work, business, shopping, education, others) and not as an average per main mode.

The VoT for the automated vehicles is determined per trip purpose, as is determined for the BTM, and is presented in Table 3-18.

Purpose/VoT	VoT in €/h
Work	8,49
Business	0
Shopping	5,37
Education	5,37
Others	5,37

Table 3-18: VoT per trip purpose for BTM and automated vehicles in the Utrecht model

The choice of using the same VoT as the BTM is supported by two main points:

- The automated vehicles are operating as BTM (besides the absence of drivers), thus, the same VoT is assumed for both modes.
- A relative research regarding the VoT for automated vehicles that could be used in this research (Yap, et al., 2015) is providing data only for the access operation of the automated vehicles to train trips and not for the egress part. Moreover, the same research defined the VoT only per mode (average VoT) and not per trip purpose, as the OmniTRANS model. Since no other relevant research has been found, from the literature conducted, upon this topic, it is chosen to use the same VoT for the automated vehicles as for the BTM of the OmniTRANS model of Utrecht.

### 3.5.2 Mode modelling

The automated vehicles are modelled as main PT mode into the Utrecht model. The main PT modes that are currently modelled in the OmniTRANS model are the train and the BTM. The reason for choosing this approach instead of modelling the automated vehicles as access/egress mode for PT relies on the easiness of modelling of the first option. However, even though the automated vehicles are modelled as main PT mode and not as an access/egress mode that is the purpose of the project, the model obtains numerous of applications in order to "translate" the automated vehicles as access/egress mode for train trips:

- Usage of penalties in order to define the access/egress relationship of the automated vehicles with the train trips.
- Dedicated modelling of the AV only between the train station of Veenendaal Centrum and the selected zones 2298, 2301, 2307 and 2310.

The respective values for the penalties and the route specifics of each case are further explained in chapter 3.5.6.

# 3.5.3 Generalized cost functions

The generalized cost functions that are used in the model of OmniTRANS are representing the disutility of the traveller using each mode. This disutility is captured as the generalised costs that a traveller is requested to pay in order to travel with each mode, expressed in the OmniTRANS model in terms of time (h). As explained in chapter 3.3, the generalized cost function of each mode involves different variables that are important for each mode to be considered (distance, in-vehicle travel time, waiting time etc.), defined with different coefficients. The generalized cost functions are linear regression expressions. Also, it is important to mention that there are two different types of generalized cost functions: 1) the generalized cost function used for the trip distribution/modal split step and 2) the generalized cost function used for the assignment step.

Due to the fact that the automated vehicles have similar characteristics and operational abilities as the BTM, the disutility functions, chosen for the automated vehicles, are the same as the ones for BTM. The respective distribution/modal split and assignment variables and coefficients, as well as their values, for the BTM are presented below (Table 3-19).

	Generalized Cost Functions							
Distribution/ Modal Split	Work	$\begin{aligned} GC_{BTM} &= \beta_1 \times V_{Distance} + \beta_2 \times V_{Time} + \beta_3 \times V_{Wait} + \beta_4 \times V_{Penalty} \\ &+ \beta_5 \times V_{Fare} \Leftrightarrow \\ GC_{BTM} &= 0 \times V_{Distance} + 1 \times V_{Time} + 0 \times V_{Wait} + 1 \times V_{Penalty} \\ &+ 0,117786 \times V_{Fare} \end{aligned}$						
	Business	$ \begin{array}{c} GC_{BTM} = \beta_1 \times V_{Distance} + \beta_2 \times V_{Time} + \beta_3 \times V_{Wait} + \beta_4 \times V_{Penalty} \\ + \beta_5 \times V_{Fare} \Leftrightarrow \end{array} $						

Table 3-19: Generalized cost functions of BTM mode of the Utrecht model

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		$GC_{BTM} = 0 \times V_{Distance} + 1 \times V_{Time} + 0 \times V_{Wait} + 1 \times V_{Penalty} + 0$
		$\times V_{Fare}$
		$GC_{BTM} = \beta_1 \times V_{Distance} + \beta_2 \times V_{Time} + \beta_3 \times V_{Wait} + \beta_4 \times V_{Penalty}$
	Shopping	$+ \beta_5 \times V_{Fare} \Leftrightarrow$
	Suppling	$GC_{BTM} = 0 \times V_{Distance} + 1 \times V_{Time} + 0 \times V_{Wait} + 1 \times V_{Penalty}$
		$+ 0,18622 \times V_{Fare}$
		$GC_{BTM} = \beta_1 \times V_{Distance} + \beta_2 \times V_{Time} + \beta_3 \times V_{Wait} + \beta_4 \times V_{Penalty}$
	Education	$+ \beta_5 \times V_{Fare} \Leftrightarrow$
Education		$GC_{BTM} = 0 \times V_{Distance} + 1 \times V_{Time} + 0 \times V_{Wait} + 1 \times V_{Penalty}$
		$+ 0,18622 \times V_{Fare}$
		$GC_{BTM} = \beta_1 \times V_{Distance} + \beta_2 \times V_{Time} + \beta_3 \times V_{Wait} + \beta_4 \times V_{Penalty}$
	Othors	$+ \beta_5 \times V_{Fare} \Leftrightarrow$
	Others	$GC_{BTM} = 0 \times V_{Distance} + 1 \times V_{Time} + 0 \times V_{Wait} + 1 \times V_{Penalty}$
		$+ 0,18622 \times V_{Fare}$
Assignment		$GC_{BTM} = \beta_1 \times V_{Distance} + \beta_2 \times V_{Time} + \beta_3 \times V_{Wait} + \beta_4 \times V_{Penalty}$
		$+ \beta_5 \times V_{Fare} \Leftrightarrow$
		$GC_{BTM} = 0 \times V_{Distance} + 1 \times V_{Time} + 1 \times V_{Wait} + 1 \times V_{Penalty} + 0$
		$\times V_{Fare}$

The  $\beta$ , which are 0, reflect the unimportance of the respective variable, and so the absence of the variable from the calculations of the generalized cost, whereas 1 means that the respective variable is important, and thus, considered in the calculation of the generalized cost. Special attention should be pointed out on the values of  $\beta_5$ , which represent the VoT, expressed in h/ $\epsilon$ . These values are then multiplied by the respective fare per mode and provide the respective variable of fare into the generalized cost function.

For the automated vehicles, the same generalized cost functions (variables and coefficients) are used as for the BTM, used by the OmniTRANS model of Utrecht. This choice is justified by three reasons:

- The coefficients (besides the one reflecting the VoT) are very simplistic (either 0 or 1), which do not allow many alterations of the coefficients for the new mode without affecting completely negative the outcomes.
- The model provides many other options in order to change indirectly the disutility of the new mode (use of penalties, speed factor).
- The great resemblance of the automated vehicles with the BTM mode allows this choice without misleading the final results.

# **3.5.4** Vehicle specifications

The automated vehicles used for this project are based on the characteristics of the ULTra automated vehicles (2getthere, 2015). So, the general characteristics of the automated vehicles are summarised in Table 3-20.

Table 3-20: Technical characteristics of the automated vehicles

Characteristics	Details
Type of Vehicle	ULTra PRT
Maximum Capacity	20 passengers (13 seating/7 standing)
Maximum Speed	50 km/h
Dwell Time	20 seconds
Energy Supply	Electric Battery

### **3.5.5** AV stops per route case

As explained in chapter 3.4.4, the route cases defined in this case study are 2. The representation of these routes is shown in Figure 3.6 of the same chapter. Though, in a more microscopic level, it is important to define the number and the location of the bus stops for the automated vehicles for each case. To this direction, two main guidelines have been developed:

- AV Stop Distances: Coverage of the investigated zones with AV stops for automated vehicles over the entire route, with average distance of each AV stop approximately 600-800 m (van Nes & Bovy, 2000).
- Choice of Existing Bus Stops: Clarification of the number of bus stops that is examined, and finally used, in the route design of both cases, and especially in the current bus line based case. This means that the automated vehicles require respective bus stops that are used for the satisfaction of their demand; however, the distance of each bus stop from the respective zones served and the radius of research for bus stops from each zone for the automated vehicles need to be clarified here. As already explained, the bus stop distance is fluctuating between 600-800 m. However, not all bus stops are relevant or useful to be used for the operation of the automated vehicles. In order to determine which bus stops are potentially functional and which not for the automated vehicles, a research area of 800 m is defined around each zone investigated. All the bus stops that are included within this area are further used as AV stops for the automated vehicles for both route cases.

Based on both points above, the final AV stop allocation per case is illustrated in Figure 3.7.



Figure 3.7: a) Left: AV stops for case 1 b) Right: AV stops for case 2

In the first case, 3 new AV stops are created, all allocated very close to the centroids of the 4 zones investigated, while for the second case, 5 new AV stops are created. In both cases, the new AV stops are allocated close to the centroids of the selected zones for 2 reasons:

- To maximize the potential demand by offering AV stops close to the centroids of the zones, and thus, serving directly the demand of the respective zones.
- Prevent the extensive walking distance for the potential demand served in all 4 zones.

A final comment is that the AV stops for both directions are at the same location, only across the street one from the other.

# 3.5.6 Model parameters

The model parameters define all the technical aspects that need specification in order for the model to reveal the output of the operation of the automated vehicles. These parameters are the new fare system of the new mode, the related penalties, waiting and dwell times per AV stop, as well as the speed, speed factor and frequencies of the vehicles.

# Fare System

The main principles of the fully automated vehicles, in terms of operation, are two: 1) these vehicles are not using drivers 2) the energy consumed is derived from electric batteries. According to Connexxion (2015), the average operational expenses for regular regional buses in terms of drivers' salaries are 60% of the total operational costs of the buses, whereas for fuel it is 10%. In addition, according to <a href="http://energy.gov/articles/egallon-how-much-cheaper-it-drive-electricity">http://energy.gov/articles/egallon-how-much-cheaper-it-drive-electricity</a>, the energy costs for fuel are approximately twice as much as for the electricity. Connecting both cost facts, the cut on operational costs could be summed up to 65% for the automated vehicles. However, since the automated vehicles still

require extra personnel for operating the systems that support their operation, it is assumed that these costs are approximately 10% of the total operational costs, leading eventually to a total decrease of the operational costs for automated vehicles by 55%. So, in order to create potential demand for the automated vehicles, this cost reduction is reflected on the fare system, introduced for the automated vehicles, which is different than the fare system of the BTM mode. It is assumed, though, that all other costs are equal in the long term operation of the automated vehicles.

The new fare system has reduced fares, compared to the current BTM fares, equal to 55%. Since the fare system of the model is using escalated fares as the distance increases, the new fares for the automated vehicles are based on the respective fare per distance used by the model for the BTM mode, reduced by 55%. Table 3-21 presents the distance (in km) and the respective fare per km for the BTM mode, as adopted by the model, and for the automated vehicles, after the fare reduction of 55% per km driven. It is worth mentioning that since the maximum distance driven by the automated vehicles is less than 20 km, the fare system is adopted until this maximum distance.

Distance (km)	Current BTM Fares (in €/km)	AV Fares (in €/km)
1	0,80	0,45
2	0,90	0,50
3	1,00	0,55
4	1,10	0,60
5	1,20	0,65
6	1,30	0,70
7	1,40	0,75
8	1,50	0,80
9	1,60	0,90
10	1,70	0,95
11	1,80	1,00
12	1,90	1,05
13	2,00	1,10
14	2,10	1,15
15	2,20	1,20
16	2,30	1,25
17	2,40	1,30
18	2,50	1,40
19	2,60	1,45
20	2,70	1,50

Table 3-21: Fare system of current BTM and of automated vehicles in the Utrecht model

# Penalties

The value of penalty into the model represents the disutility of transferring from one mode to another, either during the main trips (transfer penalties) or during the access/egress trips (access/egress penalties). The value is either a factor or an absolute value. In the case of the current OmniTRANS model of Utrecht, the value is an absolute value with max of 30, expressing the complete disutility of transfer from one mode to another, while the minimum

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value used is 0 (for walking). For transfers between PT modes, the usual value of penalty used is 7, while for the bicycle the value of 15 is adopted.

Moreover, it is important to distinguish the generic penalties used into the model and the specific penalties per stop. The first case expresses the general transfer penalties of access, egress and transfer trips from one mode to another. The second is defining in more detail the potential penalties per transit line and per transit line with the respective access/egress modes for the bus (and for AV) stops that are used.

In chapters 3.5.2 and 3.5.3, the modelling of the automated vehicles and the disutility functions used are not depicting the new mode as access/egress mode, but as a main PT mode. In order to "translate" the automated vehicles into access/egress mode for train trips, penalties are used in order to "prevent the transfer" of other modes that are not trains to the automated vehicles, with only exception the mode walking, which is not prohibited as transfer mode from and to the automated vehicles. The reason for this choice is in order to allow the pedestrians to get access to the automated vehicles (walk transfers). Though, in order to prevent the possibility of using extensive walking as access/egress mode for the automated vehicles, the respective AV stops at the train station and at the zones served by the automated vehicles are allocated to the closest distance possible, so that the model would assign the automated vehicles as access/egress modes with the minimum walking activity to the closest AV stop. Taking all the above into account, the respective generic and stop specific penalties that are used for each mode in respect to the automated vehicles are presented in Table 3-22 and Table 3-23.

Gener	Generic Penalties (for access/egress and transfer from/to automated vehicles to/from other modes)							
Modes	Modes Values of Penalties Purpose of Choice							
BTM	15,00	Intermediate penalty value in order not to completely exclude the BTM as transfer mode from/to automated vehicles.						
Car	30,00	30,00 Very high penalty value in order to completely discourage the car transfer to/from automated vehicles.						
Bicycle	30,00	Very high penalty value in order to completely discourage the bicycle transfer to/from automated vehicles (no space for bicycles within the automated vehicles).						
Train	7,00	Translation of access/egress mode choice for the automated vehicles regarding train trips. Though, still a small penalty due to the nature of transfer from one PT mode to another.						
Walking	0,00	Zero penalty value in order to encourage only walk transfers to/from automated vehicles.						

#### Table 3-22: Generic penalties for automated vehicles

Table 3-23: Stop specific penalties for automated vehicles

Stop	Stop Specific Penalties (for access/egress and transfer from/to automated vehicles						
	to/from other modes per AV and BTM stop used by automated vehicles)						
Modes	Values of Penalties	Purpose of Choice					
BTM	30,00	Very high penalty value to prevent BTM transfers from/to automated vehicles completely-automated vehicles used only as access/egress mode for train trips.					
Car	30,00	Very high penalty value because automated vehicles are used only as access/egress mode for train trips.					
Bicycle	30,00	Very high penalty value because automated vehicles are used only as access/egress mode for train trips.					
Walking	0,00	Zero penalty value to encourage only walk transfers to/from automated vehicles.					

# Waiting and Dwell Time per Stop

The waiting time is used to express the time spent waiting, on average, by passengers at the access stop, transfer stop(s) and egress stop. The value of waiting in the model could be either constant or a factor. The OmniTRANS model of Utrecht is currently using a factor of 0,5, which represents the  $\frac{1}{2}$  of the interval time of transit lines. The same approach is used for the automated vehicles for every AV stop built into the model. Though, there is only one exception: due to the fact that the automated vehicles are used as access/egress modes for train trips, this implies a need for synchronization between the schedule of trains and the schedule of the automated vehicles, which is in more detail explained in the following parts. For this purpose, the waiting time for the AV stops outside of Veenendaal Centrum is constant and equal to 2 minutes. This choice encourages the goal of synchronization, and subsequently, the perceived accuracy of transfer between the two modes, which allows the decrease of the perceived waiting time of passengers in AV stops outside the train station.

Regarding the dwell times used for each AV stop, the small vehicle capacity allows for low dwell times per AV stop. According to May, et al. (2012), the average dwell time of automated vehicles is 20 seconds, which is also representative for the regular buses. So, the dwell time used for each AV stop in this case study is 20 seconds.

# Speed

In order to define the speed of each case for the automated vehicles, the approach used for this purpose is the adoption of the average speed per link, based on the speeds currently used by other transit lines on the respective links. This process is determined for every link of each route used for the purposes of this project. Though, there are two main exceptions for this approach that need to be highlighted, and both refer to the absence of transit lines from links of the chosen routes for the automated vehicles (leading to non-availability of reference cases for the speed calculation). These exceptions are:

Link with maximum allowed speed 20 km/h: In these links it is assumed that the average speed for the automated vehicles is 10 km/h.

Link with maximum allowed speed 40 km/h: In these links it is assumed that the average speed for the automated vehicles is 20 km/h.

The usage of the 10 and 20 km/h speeds for the automated vehicles is based on the observation of the speeds of the existing bus lines in the network. Usually, the average speed of the bus lines is half of the maximum operational speed per link. In this way, for the abovementioned links that are not used by bus lines, the speed for the automated vehicles is half their maximum operational speed allowed.

# Speed factor

The speed factor is used in order to influence the travel time without changing the actual travel times. This factor could reflect different aspects: the preference of passengers over certain modes, the unreliability of a mode, the limited technological abilities of a mode and many other aspects that are difficult to be "translated" into variables, parameters or model values into the OmniTRANS model. From the survey of Yap, et al. (2015), one of the main conclusions is the operational unreliability of the automated vehicles, expressed by the participants of the survey. In order to define this expected unreliability into the model, the use of a lower, compared to the current, speed factor is used. The current speed factor is 1, so for the purposes of this project, the new speed factor per route investigated is lowered to 0,9.

# Frequencies

The frequencies that are used for the automated vehicles are following the schedule of trains in Veenendaal Centrum, as already inferred above. With the use of the NS website (http://www.ns.nl/reisplanner-v2/index.shtml), the train schedules for all train directions are on average the same: for morning and evening peaks the frequencies are 4 trains/hour/ direction, while for the rest of the day is 2 trains/hour/direction. Since the goal is to synchronize the schedules of trains and automated vehicles, and inevitably express the operation of the automated vehicles as access/egress modes for train trips, the respective frequencies per time period for the automated vehicles should be the same as the ones for the trains for both directions of each case. However, it is important to define also the minimum number of vehicles required for accomplishing these frequencies. For this purpose, the total travel time of the automated vehicles, in respect to the schedule of the trains. The calculation of the number of vehicles per route case is explained in detail in chapter 3.5.7.

# 3.5.7 Number of vehicles

In order to determine the minimum required number of automated vehicles, so that the frequencies mentioned in the previous chapter would be accomplished, it is essential to use as input three main points:

> The total travel time per route for the automated vehicles.

- The schedule of the trains between Utrecht Centraal and Veenendaal Centrum (assuming that this is the busiest and more demanding train route in Veenendaal Centrum).
- The minimum waiting time of the automated vehicles at the train station in order to assure connectivity of passengers to/from trains with the automated vehicles.

For the first point, the travel times derive from the model for each case. The total travel time for each of the 2 cases investigated are shown in Table 3-24. Regarding the schedule of the trains, the use of the Utrecht Centraal-Veenendaal Centrum-Utrecht Centraal train schedules are used, assuming that these trains are the most representative of the entire passenger flow at Veenendaal Centrum station. The schedules for each time period (and more specifically for an hour per time period) are derived from the NS website (<u>http://www.ns.nl/reisplanner-v2/index.shtml</u>). Finally, the minimum waiting time of the automated vehicles at Veenendaal Centrum is 4 minutes, counting from the moment the train from Utrecht Centraal arrives in Veenendaal Centrum. This time is used in order to provide an acceptable timeframe for passengers getting out of the train until they reach the AV stop. It is assumed that this time is enough for walk transfer between train and automated vehicle, since the respective AV stop outside the train station is very close to the train station (less than 150 m).

#### Table 3-24: Route travel times per case

	Case Travel Times For Automated Vehicles
Case 1	Route Travel Time <sub>AV1</sub> = Travel Time <sub>Direction</sub> $\times 2 \Leftrightarrow$ Route Travel Time <sub>AV1</sub> = 30,10 $\times 2$ = 60,2 minutes
Case 2	Route Travel Time <sub>AV2</sub> = Travel Time <sub>Direction</sub> $\times 2 \Leftrightarrow$ Route Travel Time <sub>AV2</sub> = 26,60 $\times 2$ = 53,20 minutes

The representation of the schedule for the trains and the respective schedule for the automated vehicles for each of the cases are realised via time-space diagrams. There are two types of time-space diagrams created: the first is for the trains for 1 hour of operation each period (morning peak, evening peak and rest of the day) and the second for the respective 1 hour of operation of the automated vehicles, for each one of the 2 routes investigated (with the respective travel times and the minimum of 4 minutes waiting time from the arrival of the Utrecht Centraal train and the departure of the automated vehicle from the train station). Below, the time-space diagrams for the trains and the automated vehicles are presented for the morning peak for cases 1 and 2 (Figure 3.8).



Figure 3.8: a) Up: Time-space diagram for the Utr. Centraal-Veenendaal Centrum-Utr. Centraal train in the morning peak b) Down-Left: Time-space diagram for automated vehicles in case 1 in the morning peak c) Down-Right: Time-space diagram for automated vehicles in case 2 in the morning peak

All the rest time-space diagrams created are shown in Appendix C. The purpose of these diagrams is dual: 1) to assure the synchronization that is desired for the two mode schedules and 2) to determine the number of automated vehicles required based on the schedule and the frequencies chosen for the new mode. The outcome of the time-space diagrams showed some interesting points:

- During non-peak periods (rest of day), the minimum number of vehicles required is 3 for case 1 and 4 vehicles for case 2.
- During peak hours (morning and evening), the minimum number of vehicles required is 4 vehicles for both cases.

So, the minimum number of vehicles for both cases is 4. However, it is important to highlight that the number of vehicles calculated at this point is not related to the number of expected passengers for the automated vehicles. After the run of the model and the determination of

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the demand for the automated vehicles for each of the 2 cases, a re-evaluation of the number of vehicles required is made, in order to adjust the supply (number of vehicles and potentially frequencies as well) with the respective demand (number of expected travellers with the automated vehicles).

# **3.6 Conclusions and Recommendations**

This chapter elaborated on three main directions. Firstly, the case study of the province of Utrecht is introduced, while the respective OmniTRANS model of Utrecht is explained. Moreover, the execution of the identification/design process in the province of Utrecht is presented, as determined in the methodology in chapter 2, in order to reveal the highest potential train station-zones-route combination/cases (Parts A and B of the methodology). Finally, the model setup is developed, based on the outcomes of the identification and design and the possibilities offered by the respective model of Utrecht.

All the steps mentioned revealed that Veenendaal Centrum is the train station that has the highest possible potential. The chosen zones of Veenendaal Centrum that have the highest potential for hosting the automated vehicles are zones 2298, 2301, 2307 and 2310. Finally, the routes designed for connecting Veenendaal Centrum and the 4 chosen zones are based on 2 route scenarios, namely the current bus line based and the shortest path based routes. Each route is modelled and represented based on the model setup that is defined in chapter 3.5. So, the train station-zones-routes cases that are further evaluated in chapter 4 are 2.

Throughout the case study, different decisions and simplifications are made, due to a variety of reasons (limited time, lack of data, high running time of the model, the simplicity of the model etc.). Starting with Parts A and B, executed in the case study, only 2 cases are determined. This decision is made for the purposes of this project due to limited time, in combination of the high running time of each case by the model. However, this choice could be altered by other research studies, so that all possible cases could be examined and evaluated:

- More cases involving different number of potential zones per case (and not only the 4 zones chosen for both cases) could provide more options for evaluation, and thus, determination of the best possible case from a wider set of cases.
- The 2 route scenarios (current bus line based and shortest path based) used in this case study could be extended to other route options that could connect Veenendaal Centrum with each of the zones, such as routes that operate through city centres of these zones or highways. In this way, different network aspects could be captured, and so, the determination of the maximum possible potential route out of a wider set of potential routes.

Moreover, based on the methodology (chapter 2.2.4), the choices regarding the potential train station-zones-routes cases requested checking, and this is the reason for performing a sensitivity analysis and a validation. Though, certain points need to be highlighted regarding both processes:

- For the sensitivity analysis, different weights per criterion are requested, and not only for criterion 2.1, so that the importance and influence of each criterion would be tested, and thus the robustness of the outcomes would be further investigated. This process would assure the choice of the number of zones used per case, and especially when applying the maximum potential zone to a case, a decision that requests more robust and concrete outcomes.
- Regarding the validation process, although Veenendaal Centrum and its respective zones are highly potential candidates, also other zones, namely in Abcoude, Veenendaal De Klomp, Amersfoort Vathorst, Bunnik and Den Dolder train stations, are also considered as strong candidates. Thus, a future research could examine all these choices as well and compare the outcomes of each case study with the one in Veenendaal Centrum in terms of demand and cost-benefit ratio.

For the model set up for both cases (chapter 3.5), a lot of simplifications and assumptions are made, because of lack of data and limited abilities of the model. The lack of data is mostly related to the fact that the operational framework of the automated vehicles is a new concept, with limited investigations upon this topic. So, some of the points that would request future investigation are the following:

- More investigation is required, regarding the influence of different aspects upon the disutility function of the new mode. For instance, the relationship between the passengers' feeling of security when using the automated vehicles (considering that the concept adopted in this research is the use of fully automated vehicles) and their final mode choice is a point that is not examined yet, and thus, not incorporated to this project. Moreover, aspects such as the comfort offered by these modes, the level of operational reliability or even the possibility of using a different VoT for automated vehicles than the one from the BTM mode used in this project, are not examined here. All these points request special attention by future researches, so that their level of influence to the passengers' mode choice would be determined, and thus, modelled via the disutility function of the automated vehicles.
- The modelling of the automated vehicles as an access/egress mode for PT, instead of main PT mode choice as in this project, would provide data that are not captured by this model set up. For instance a) the modal split of access/egress mode choices for train trips, including also the automated vehicles as access/egress mode, b) the total volumes of train users that switch to automated vehicles, c) the accurate determination of the car and bicycle users that switched to PT as main mode choice and to automated vehicles as access/egress mode choice etc. are not captured by this model.
- The use of more "detailed" coefficients (rather than 0 or 1 that is mostly used in this model) in all disutility functions in the OmniTRANS model is a point that requests further investigation and data. The availability of more sophisticated coefficients per variable, especially for the total travel time and fare variables, would determine the mode choice in a more accurate way, by taking into account the sensitivity of passengers over each mode per variable.
- The use of vehicle specifications that are not based on the available technology. Although the entire project is not constraint by the current technologies, still the

vehicle specifications are based on an existing automated vehicle structure, namely the vehicle ULTra. This vehicle structure limits the potential abilities of the new mode to specific speed abilities (maximum 50 km/h) or capacity limitations (maximum 20 passengers). Future research could be developed to determine different technological abilities for the automated vehicles, and thus, test how the vehicle specifications affect the final outcome and in which level.

A final comment regarding this chapter is related to the alterations of the existing transport network, derived from the implementation of the automated vehicles. Two main points request attention:

- The automated vehicles use the existing infrastructure, without implementing further adjustments but the AV lines and stops.
- No replacement of any mode is realised in both cases developed for the automated vehicles. This means that the car, bicycle, pedestrians and PT network remain as in the current situation.

This latter point highlights the fact that this project has not investigated the potential of replacing an existing mode, and especially bus lines that operate around the network examined in this case study (Veenendaal Centrum and the 4 associated zones). This generates new opportunities for future researchers:

- Development of a methodology that identifies potential bus lines that could be replaced by automated vehicles, with special focus on the low demand bus lines. Criteria such as the on-board passengers per bus line, the frequencies, the boarding/alighting volumes per bus stop and the regional setting of operation (rural area or city) could be used as input for the methodology.
- Modelling of the automated vehicles as replacements of existing bus lines, in addition to their new dedicated routes, as determined by the methodology developed in this project.
- Examination of the potential "reaction" of the transport network, in terms of demand and costs-benefits (following the evaluation process that is defined in chapters 2.4.1 and 2.4.2), after the replacement of existing bus lines by automated vehicles.

# 4 APPLICATION OF METHODOLOGY PART C

# 4.1 Introduction

After the determination of the train station-zones-routes combinations (Part A) and the two cases (Part B) defined in chapter 3, in this chapter, each of the two cases is examined and evaluated for its potential output (Part C). Basically, the results of the evaluation are directed in two ways: a) the presentation of demand-related output (AV users, train users, access/egress mode choices from/to Veenendaal Centrum and zones' modal split) b) the cost-benefit analysis (CBA) of the involved system for both cases, namely the stakeholders/perspectives that are influenced by the introduction of the automated vehicles and the way they are influenced. Finally, conclusions regarding the results are generated.

# 4.2 Demand-Related Results

The first step of the evaluation process is the application of the 4 demand-related criteria, as determined by the methodology in chapter 2.4.1, in the case study of Utrecht. Here, a detailed elaboration on changes of demand is presented, regarding the AV passengers, the train trips before and after the implementation of the AVs, the modal split of the access/egress mode choices from/to train station of Veenendaal Centrum and the modal split of the zones covered by the automated vehicles (2298, 2301, 2307 and 2310).

# 4.2.1 AV users

The implementation of the two cases (current bus line based route and shortest path based route) in the model has generated demand for automated vehicles. The level of demand is identified by the interpretation of the on-board passengers per AV stop for each of the two cases examined in this project, as well as through the determination of the boarding/alighting volumes for each stop. Moreover, both directions of the route are examined in terms of demand, in order to perceive the volumes and the potential flow directions between the four zones served by the automated vehicles (2298, 2301, 2307 and 2310) and the train station of Veenendaal Centrum. Furthermore, for each case and each direction examined, the volumes are given for a regular working day, spread for the three main time periods: morning peak, evening peak and rest of the day. It is important to highlight two main points:

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- The morning and evening peak are considered to last 2 hours each, whereas the rest of the day is considered as 14 hour operation. So, the total operational time for the automated vehicles (an assumption that is also used for the BTM) is 18 hours.
- The data reflecting the volumes (boarding, alighting and on-board passengers) are provided for the entire time period examined and not per hour. Also, the results reflect the total demand per time period for the given frequencies, namely for the entire 4 vehicles/hour for peak periods and 2 vehicles/hour for the rest of the day.

The results for each case regarding the general boarding, alighting and on-board passengers per direction and time period are presented in Table D-1 and Table D-2 in Appendix D.1.

As depicted in Table D-1 and Table D-2, both cases have considerable demand in total per time period and direction. For both cases, the first direction is serving more passengers for the entire day, compared to the second direction. Moreover, the total boarding/alighting passengers for both cases in the morning peak are lower than the respective volumes in the evening peak for both directions (for instance for the first case and for the first direction, approximately 60 passengers use the automated vehicles during morning peak, whereas in the evening peak approximately 110 passengers are served). This inequality between morning and evening period is explained in two ways:

- All 4 zones during the analysis part in chapter 3.4.2, revealed high number of trips for shopping and other purposes during the rest of the day, which means that some of these trips are captured during evening peak as return-to-base trips.
- In order to justify the above mentioned reasoning and also to define this trip pattern regarding these zones, bus lines 80, 81 and 83, serving currently the zones, are examined in the same way. The outcome of this examination shows that especially lines 80 and 81 follow the same pattern, namely far more trips during the evening peak are produced, compared to the morning peak.

For both cases, the inflow and outflow passengers for the four zones served is considerably high (stops Veenendaal 2298, Veenendaal 2301, Veenendaal 2310 and Veenendaal 2307 for both cases) (Figure 4.1 and Figure 4.2). There are slight differentiations between each case regarding the number of boarding and alighting passengers per zone. The most interesting one is the alighting passengers of zone 2298 in case 1, with approximately 130 passengers, the maximum number of passenger flow among all zones in case 1. For case 2, the highest number of boarding and alighting passengers among all zones is for zone 2301, with approximately 120 and 110 passengers respectively. For the first case, this could be explained by the fact that the automated vehicles connect now zone 2298 directly with the other 3 zones on the chosen route, something that is not currently achieved. As for the second case, zone 2301 has high number of total trips (chapter 3.4.2), which are now served in lower travel time and distance, which generates more AV trips in case 2 than in case 1.



Figure 4.1: Boarding/alighting passengers for zones in case 1



Figure 4.2: Boarding/alighting passengers for zones in case 2

Though, the most significant fact regards the passenger interactions at the train station (stop 1216, Veenendaal Station Centrum Kerkewijk). For the first case, more passengers board or alight at the train station stop for both directions (approximately 300 passengers in total per day), compared to the second case (approximately 200 passengers in total per day) (Figure 4.3). A possible explanation for this is that the bus stops currently used by bus lines and

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automated vehicles for the first case serve existing demand on all four zones. So the automated vehicles, since they are serving more or less the same stops as the existing BTM lines, there is already an existing demand captured by these stops, compared to the second case, where most of the AV stops are new, and thus, not capturing directly existing demand. In summary, the higher connectivity offered in case 1, compared to case 2, is outweighing the shorter travel distance advantage of case 2.



Figure 4.3: AV passengers from Veenendaal Centrum train station per case per day

Figure 4.4 illustrates the total AV passengers per case for the entire day of operation (both directions included). According to these summarised output data, the first case is serving approximately 600 passengers per day, while the second case approximately 500 passengers per day.



Figure 4.4: Total AV passengers per case per day (both directions)

Methodology for assessing the potential of using automated vehicles as an access/egress mode for train trips in a regional setting-An application to the province of Utrecht This difference in total passengers, in addition to the different passenger volumes per time period and direction for each of the two cases (Table D-1 and Table D-2), could be justified by two main facts:

- The number of AV stops for the first case is higher (higher connectivity) than the AV stops for the second case, covering in this way more potential demand.
- The connection of currently used bus stops in the first case provides already an existing demand that is served by BTM lines for the same routes and bus stops, compared to the second case in which more new AV stops are created and less existing demand is captured by currently operating bus stops.

In order to provide a better insight of the results, the total boarding and alighting volumes are projected into demand per vehicle for each time period, taking into account the frequency per time period. In this way, the average boarding/alighting volumes per vehicle are determined, and subsequently, the average load per vehicle for one single route per period. These averages determine also whether the number of vehicles, calculated for the purposes of the project (chapter 3.5.7), are sufficient or require adjustments (given the total capacity of 20 passengers per vehicle, determined in the same chapter). The respective passengers per vehicle per time period, direction and case, are presented in Table 4-1.

According to Table 4-1, the busiest time period for the automated vehicles is the evening peak. The vehicles for both cases in that time period are serving a number of passengers more than half the capacity of the vehicle for both directions (starting from 10 passengers/vehicle for direction 1 in case 2 and reaching volumes of 15 passengers/vehicle for case 1 for direction 2). Regarding the other two time periods, all vehicles are serving volumes lower than half of the offered vehicle capacity (20 passengers on-board). The rest of the day time period is serving the lowest demand of the entire day for both cases (maximum demand for the rest of the day period is 5 passengers/vehicle for case 1 and direction 2).

Besides providing a better overview of the boarding/alighting volumes for the automated vehicles, Table 4-1 is used as reference for determining the potential supply of automated vehicles. So far, the maximum number of vehicles required for both cases in order to provide synchronized service with train trips, is 4 vehicles per case (chapter 3.5.7). Taking into account, also, the given capacity per vehicle (in total 20 passengers on board), the average volumes per vehicle and time period of Table 4-1 are complying with this prerequisite. This means that the demand derived from the model is not requesting for purchasing more vehicles than the 4 vehicles per case, as determined in chapter 3.5.7. Though, in order to assure that the supply is sufficient according to the demand, the same approach, as applied in Table 4-1 for the average demand per period for the entire route, is applied also for each AV stop, in order to define the on-board volumes per stop for both cases. The outcome of this investigation led to the conclusion that the demand (on-board loads) is lower than the given capacity of the vehicles, as determined earlier.

#### Table 4-1: AV users per vehicle per hour

Direction 1 Zone 2298->2307									
	Morning Peak Frequency (Vehicles/h)	Morning Peak Total Demand (for 2 hours operation) (# of Passengers)	Morning Peak Demand Per Hour (Passengers/Ve hicle)	Rest of Day Frequency (Vehicles/h)	Rest of Day Total Demand (for 14 hours operation) (# of Passengers)	Rest of Day Demand Per Hour (Passengers/Ve hicle)	Evening Peak Frequency (Vehicles/h)	Evening Peak Total Demand (for 2 hours operation) (# of Passengers)	Evening Peak Demand Per Hour (Passengers/Ve hicle)
Case 1: Current Bus Line Based Route	4	63	9	2	127	5	4	108	13
Case 2: Shortest Path Based Route	4	48	6	2	108	4	4	80	10
				Direction 2: Zon	e 2307->2298				
	Morning Peak Frequency (Vehicles/h)	Morning Peak Total Demand (for 2 hours operation) (# of Passengers)	Morning Peak Demand Per Hour (Passengers/Ve hicle)	Rest of Day Frequency (Vehicles/h)	Rest of Day Total Demand (for 14 hours operation) (# of Passengers)	Rest of Day Demand Per Hour (Passengers/Ve hicle)	Evening Peak Frequency (Vehicles/h)	Evening Peak Total Demand (for 2 hours operation) (# of Passengers)	Evening Peak Demand Per Hour (Passengers/Ve hicle)
Case 1: Current Bus Line Based Route	4	65	8	2	131	5	4	117	15
Case 2: Shortest Path Based Route	4	55	7	2	103	4	4	92	11

# 4.2.2 Train users

An important aspect of the implementation of the automated vehicles is their effect on train trip volumes in train station Veenendaal Centrum. The volumes per day for access and egress trips at the train station for the current situation and for the two cases are presented in Table 4-2, while the respective differences for both cases compared to the current situation, based on the outcomes (rounded) of Table 4-2, are presented in Figure 4.5.

Train Trips of Veenendaal Centrum						
		Morning Peak	Rest of the Day	Eveneing Peak	Total Trips	
Current	Access Veenendaal Centrum	1000	900	500	2400	
Situation	Egress Veenendaal Centrum	400	1000	700	2000	
Case 1: Current Bus	Access Veenendaal Centrum	1000	900	500	2400	
Line Based Route	Egress Veenendaal Centrum	400	1000	700	2000	
Case 2: Shortest Path Based Route	Access Veenendaal Centrum	1000	900	500	2400	
	Egress Veenendaal Centrum	400	1000	700	2000	







Methodology for assessing the potential of using automated vehicles as an access/egress mode for train trips in a regional setting-An application to the province of Utrecht The outcomes are interesting and completely different for the two cases. On one hand, for the first case, the operation of the automated vehicles has generated new train trips (in total almost 20 passengers per day more than in the current situation are accessing or egressing train station Veenendaal Centrum). On the other hand, for the second case, there has been significant decrease of train trips per day (almost 40 train travellers less in total, compared to the current situation). The reduction of train trips for the second case could be explained by the fact that the second route case is avoiding a lot of currently used bus stops, so lower connectivity offered by case 2, compared to case 1. This means that a fact like that might restrain current bus users to new bus stops in the second case that are not as attractive as the bus stops used at the moment at the first case.

# 4.2.3 Access/egress mode choices from/to Veenendaal Centrum

Besides the volumes regarding the automated vehicles and the train, it is essential to identify the changes regarding the mode choice for access or egress trips for train trips. In Figure 4.6 and Figure 4.7, the potential changes in terms of passengers' volumes per access/egress mode outside Veenendaal Centrum train station are presented for each case. The most significant changes occurred for BTM travellers, which seem to have switched for their egress trips to automated vehicles in the first case, summing the AV egress trips to approximately 20, while the 6 access trips with automated vehicles are coming from the car switch that occurred (Figure 4.6).



Figure 4.6: Access/egress mode choice changes outside Veenendaal Centrum train station for case 1

On the other hand, the second case serves very few passengers from/to the train station with automated vehicles, namely 6 travellers per day, with very few access/egress mode choice changes from/to train station (Figure 4.7). The differences in AV volumes between

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the two cases is partially explained in chapter 4.2.2, where the total train trips in the second case are reduced significantly, whereas in the first case they have been increased, affecting in this way also the access/egress mode choices of users outside Veenendaal Centrum.



Figure 4.7: Access/egress mode choice changes outside Veenendaal Centrum train station for case 2

# 4.2.4 Zones' modal split

The focus of this part is on the current modal split of the zones that are potentially served by the automated vehicles, namely zones 2298, 2301, 2307 and 2310, and their differentiation between the two cases and the current situation (Figure 4.8-Figure 4.11). The modal split involves the 3 main mode choices, namely the car, the bicycle and the public transport, in the latter of which the automated vehicles are included in cases 1 and 2.



Figure 4.8: Left: Modal split of zone 2301 currently-Right: Modal split changes in zone 2301 for case 1 and 2



Figure 4.9: Left: Modal split of zone 2298 currently-Right: Modal split changes in zone 2298 for case 1 and 2



Figure 4.10: Left: Modal split of zone 2307 currently-Right: Modal split changes in zone 2307 for case 1 and 2



Figure 4.11: Left: Modal split of zone 2310 currently-Right: Modal split changes in zone 2310 for case 1 and 2

As can be observed, the modal split is slightly changed for both cases, compared to the current situation, presenting a positive reaction (increase) for the public transport mode choice and a negative impact (decrease) regarding the car and the bicycle choice for all of the four zones. The lowest positive change in the public transport share has occurred for zone 2301 (+ 0,18% for the first case and + 0,22% for the second case, compared to the initial situation), whereas the highest impact has been identified for zone 2298 (+ 0,45% for the first case and + 0,55% for the second case, compared to the initial situation). This increase in the PT share for all zones in both cases is due to the AV operation. These percentages are derived from mode change occurred in both the car and the bicycle users in both cases, though the decrease of the car share in both cases and for all zones is slightly lower than the decrease of the bicycle share. However, it is interesting to mention that the

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decrease of the car and bicycle share in the second case for all zones is higher than for the first case.

It is important to highlight the fact that the changes are more significant for all zones in the second case, rather than in the first case. However this contradicts the outcomes of the previous parts (chapters 4.2.1, 4.2.2, 4.2.3), where the second case has lower values for all 3 criteria used in terms of demand, compared to the first case. Nevertheless, the higher modal split share for the second case could be explained by two points:

- The modal split changes for the car and the bicycle are higher in the second than in the first case for all zones examined, so the switch to PT in the second case is also higher. This means that for the second case, more users of all the O-D pairs involving the 4 zones might have changed their main mode choice from the car and the bicycle to PT, due to the implementation of the automated vehicles, than for the first case.
- The upper point could be justified also by the fact that the route of the second case is shorter than in the first case, which means lower travel time, so more attractive for the potential AV user to choose the new mode as access/egress mode, and so, choose the PT as main mode of transport.

Although the abovementioned changes have not influenced the modal splits more than 1% for each main mode for each zone, it is important to consider that the modal split of these zones are depicting the entire production and attraction of trips for the whole province of Utrecht. Thus, these percentages could be considered as rather significant, taking into account that:

- The automated vehicles are serving a very small route and number of zones in both cases.
- The new mode is used as an access/egress mode for train trips, so basically for lastmile trips, dedicated only to train trips.

# 4.3 New System Related Results: Cost-Benefit Analysis

This part of the evaluation of the case study of Utrecht is focusing on the effects of the automated vehicles in a more systematic approach, namely identifying changes in relation to transportation, financial aspects of this new investment and environmental impacts. The starting point is the description of the framework of the CBA, the time horizon and the main assumptions used, followed by a thorough description of each of the 14 evaluation criteria derived from the methodology in chapter 2.4.2. Finally, the CBA is performed and the respective results are discussed further more.

# 4.3.1 CBA framework

The systemic cost-benefit analysis that is conducted at this project is aiming for a better insight on the costs and benefits that the new transport system creates to different perspectives/stakeholders, based on the outcomes of the case study of Utrecht (chapter 3).

The cost-benefit analysis is trying to combine 5 different perspectives: a) the passengers, b) the AV operator, c) the BTM operator, d) the society and e) the government of the Netherlands. Each of these perspectives is affected by different criteria, which are in total 14 in this CBA evaluation process. These criteria are reflecting the effects on 6 aspects: investment costs, fare effects, operational effects, externalities, levy and travel time effects (chapter 4.3.4).

The goal of this chapter is to determine the Net Present Value (NPV) between the existing situation and each of the two cases, which both include the automated vehicles, for the year of 2010 and projected further to the time horizon decided for the CBA in chapter 4.3.3. Finally, it is essential to pre-determine at this point which modes are examined, besides the automated vehicles, in this CBA. For the purposes of this evaluation process, besides the automated vehicles, also the changes in respect to the car and the BTM modes are included. The reason for choosing these three modes for the CBA and not include also the bicycles is because of two important points:

- There are not many monetary values connected to the changes of bicycle users (at least from the so far literature review).
- The changes on the bicycle mode choices are assumed to be not of importance for the purposes of this CBA.

# 4.3.2 Assumptions

In this CBA, certain assumptions are pre-determined, regarding the data used and the approach followed. All the assumptions are summarized below:

- 1. The CBA is not technologically constraint, meaning that the automated vehicles both in the present and the future are having similar operational abilities as the BTM currently, without constraining the new mode by the current technologies applied.
- 2. The annual interest rate for the Netherlands is constant every year and equal to 5,5%, which is applied to the Present Values of the CBA time horizon for each criterion, based on the general equation (Verhaeghe, 2013):

$$\frac{PV_t}{(1+i)^t}$$

where:

t: The time of the cash flow (2040)

*i*: The interest rate (in this case 5,5%)

 $PV_t$ : The net cash flow i. e. cash inflow – cash outflow, at time t (in 2040)

- 3. The input data are projected to the CBA time horizon for the entire lifetime of the automated vehicle project.
- 4. The demand for all modes involved in the CBA is considered to be constant per year through the entire time horizon of the project.
- 5. The effects for all modes are calculated as whole for the entire 5 working days per week, whereas for the 2 days of the weekend, it is assumed that the effects are half

per day, compared to the effects during weekdays. This means that all modes are assumed to operate in total 6 days per week.

# 4.3.3 Time horizon of CBA

The CBA is having as implementation starting point the year of 2010, namely the year in which the input data of the model are derived, and as endpoint the year of 2040. This choice of the 30 year time horizon for this CBA is binary:

- 1. Provide enough timeframe for the automated vehicles to overcome the investment costs of the first years.
- 2. The timeframe of 30 years is the lifetime of an automated vehicle project (Young, et al., 2009). So, based on this, the CBA that is conducted is trying to determine, besides the trends for the automated vehicles, also the respective trends for cars and BTM for the investigated time period.

# 4.3.4 Evaluation criteria for CBA

After the determination of the main guidelines of the CBA above, this part is elaborating on the evaluation criteria that are included in the CBA with a detailed description of them and their respective references. As already mentioned in chapter 4.3.1, there are 5 main perspectives/stakeholders affected and involved in the operation of the new mode: passengers, AV operator, BTM operator, society and government. Each of these stakeholders is related to one or more out of the total 14 evaluation criteria for the CBA (chapter 2.4.2). In the next parts, each evaluation criterion is described for each of the stakeholder involved.

# Passengers' perspective

The main effect categories that are examined for the passengers' perspective are 2: 1) the fare effects and 2) the travel time effects. The corresponding criteria for these categories are: 1) Passenger (fare) effects of former BTM users switched to automated vehicles, 2) Passenger (fare) effects of former car users switched to automated vehicles, 3) Passenger (fare) effects of other mode users switched to automated vehicles, 4) BTM in-vehicle time effects, 5) BTM waiting time effects and 6) Car in-vehicle time effects. All 6 criteria are in detail described below:

1. Passenger (fare) effects of former BTM users switched to automated vehicles: Here, the fare effects are calculated for the BTM users that switched to the automated vehicles. These fare effects are dependent on the daily demand switched from one mode to another. This daily demand difference is translated into monetary fare effects by applying the fare difference between the fare system of the BTM and the fare system per travelling km of the automated vehicles, as established in chapter 3.5.6. Moreover, the daily monetary fare effects are projected for the year of 2040 (Present Value), namely the time horizon of the CBA (Table D-3). For reasons of simplicity, the BTM user changes are assumed to be realised on 3 BTM lines (80, 81

and 83) that connect the 4 selected zones (2298, 2301, 2307 and 2310) and across these routes only and not across the entire BTM line routes in the network. So the respective BTM lines are examined for the stops that are associated to these zones (which bus stops are the same or close to the AV stops for both cases). For these BTM stops, the demand changes and monetary fare effects are calculated. More detailed description of the fare effects determination is available in Appendix D.2.

- 2. Passenger (fare) effects of former car users switched to automated vehicles: For this criterion, the daily demand switch from car to automated vehicles is calculated per case and translated into monetary fare effects, by applying the fare difference between the fuel price per litre/travelled km car users used to pay and the fare per km for using the automated vehicles, based on the fare system established in chapter 3.5.6. The final step is the projection of the daily monetary fare effects for the car switched demand to the Present Value of year 2040 (Table D-4). The car demand changes are examined for the entire car network of the area of Utrecht. Further explanation of the input data and approach used for this criterion are presented in Appendix D.2.
- 3. Passenger (fare) effects of other mode users switched to automated vehicles: Besides the BTM and car users that switched to the automated vehicles, also other mode users switched from their current mode choices to the new mode. Examples are pedestrians, cyclists, new AV users and BTM users that switched to the automated vehicles and travel along longer routes than they used to with the new mode. Regarding this latter mode choice, it is important to point out that AV stops are modelled closer to the 4 selected zones, so potential AV users are reaching these zones with less walking distance than from the regular BTM stops. The approach of determining this extra demand for automated vehicles is the following: the total demand for automated vehicles is calculated per case (Table D-5 and Table D-6) and subsequently the demand difference of BTM and car users of the previous 2 evaluation criteria is subtracted from the total AV demand. In this way, the daily demand for automated vehicles from other mode users is determined for each case and further translated into daily monetary fare effects, by using the fare system of the automated vehicles (chapter 3.5.6). The final step is the calculation of the Present Value of these fare effects for the year of 2040 (Table D-7). All these data are processed and presented in more detail in Appendix D.2.
- 4. <u>BTM in-vehicle time effects BTM waiting time effects:</u> Here, the in-vehicle and waiting travel time effects of the BTM system are determined, after the introduction of the automated vehicles for each of the two route cases (Table D-9). In order to define the in-vehicle and waiting travel time effects, the daily in-vehicle and waiting travel time difference is calculated for the entire BTM system of the area of Utrecht for each of the two cases, compared to the current situation (without automated vehicles). These travel time changes are translated into monetary values (Present Value) with the use of the VoT of the BTM, as currently used by the OmniTRANS model. All the above are in detail presented in Table D-9 in Appendix D.2.
- 5. <u>Car in-vehicle time effects</u>: Following the same idea as in criterion 4 for the BTM travel time effects, in this criterion the car in-vehicle travel time effects are calculated for each case, in comparison to the current situation. This travel time effects are determined for the entire car network of the area of Utrecht and are

projected to the year of 2040 (Present Value). All the above are in detail presented in Appendix D.2.

# AV operator's perspective

Regarding the AV operator's perspective, there are 3 main categories with 4 evaluation criteria in total used for the CBA, all of them related to the financial aspect of the introduction of the automated vehicles to the transport system. These aspects are the investment costs, the fare effects and the operational effects. The respective criteria are: 1) the construction costs of new AV stops, 2) the purchase of the automated vehicles, 3) the fare effects from all AV users and 4) the operational and maintenance costs of the automated vehicles. All these financial aspects are examined for each case:

- 1. <u>Construction costs of new AV stops</u>: Each case requests the construction of new AV stops in order to satisfy potential demand (chapter 3.5.5). The total construction costs for the new stops per case are depicted and explained in Table D-10 in Appendix D.2.
- 2. <u>Purchase of the automated vehicles</u>: The purchase costs per vehicle for each of the two cases are calculated and included in the CBA. The total purchase costs per case are depicted in Table D-11 in Appendix D.2.
- **3.** <u>AV operator (fare) effects from all AV users:</u> The fare effects captured by the AV operator are the respective fares payed by all AV users. In this criterion, the total AV demand is calculated (former BTM users, former car users, former pedestrians, former cyclists and new AV users). This daily demand is translated into monetary fare effects for each case with the use of the AV fare system (chapter 3.5.6). Finally, these monetary effects are translated into Present Value for the year of 2040. More detailed explanations are presented in Appendix D.2.
- 4. <u>AV operational and maintenance costs</u>: The operational and maintenance costs regarding the new system are determined and included in the CBA for each of the two cases. These costs are annual costs and projected, eventually, to the year of 2040. Detailed explanation of the input data and cost definition is presented in Table D-12 in Appendix D.2.

# BTM operators' perspective

The changes in the BTM users affect also the revenues (fare effects) of the BTM operators. So, in order to capture this revenue change, the BTM fare effects for the operator are identified:

1. <u>BTM (fare) effects for operator</u>: As already mentioned in the passengers' perspective, the switch in mode choice from BTM to automated vehicles has generated revenues for the AV operator, but loss for the BTM operators. So, the positive Present Value determined for the passengers' perspective for BTM fare changes is a respective negative Present Value for the BTM operators. This equal but opposite value is also included into the CBA, in order to capture the influence of the automated vehicles to the BTM operators, in addition to the BTM passengers.
Detailed determination of the quantitative input data for the CBA is presented in Table D-9 in Appendix D.2.

As a final comment, the BTM lines that are currently operating in the network are assumed to continue to operate in the same way as in the reference situation. This means that the automated vehicles are not replacing any BTM lines, at least for the purposes of this project. This inevitably leads to the conclusion that the operational and maintenance costs for the BTM lines remain the same as currently. For this reason, they are not included in the CBA.

#### Society's perspective

An important aspect of the new system is the potential gains of the implementation of the automated vehicles in terms of externality effects. The focus of the externalities is on both carbon and non-carbon pollution costs for the automated vehicles and for the car (again, the BTM lines remain unchanged, so no alterations for the respective externalities as well). Both effects are explained below:

- 1. <u>AV externality effects</u>: Although automated vehicles are considered to have far less externalities, still they produce emissions that need to be examined in the CBA. The respective externality costs for each case in both annual and 30-year time horizon are in detail presented in Table D-13 in Appendix D.2.
- 2. <u>Car externality effects:</u> With the implementation of the automated vehicles, there has been a mode change from the car to the new mode, as seen in the passengers' perspective, which means changes for the externality costs derived from the car between the reference case (without automated vehicles) and each of the two cases. These changes in externality costs are shown in Table D-14 in Appendix D.2 for each of the two cases in an annual and 30-year time horizon.

#### Government's perspective

The final perspective that is taken into account for the CBA is the government. In this perspective, the levy effects are determined:

1. <u>Levy effects:</u> The switch of car users to the automated vehicles before and after the implementation of the automated vehicles has subsequently influenced the levy revenues of the government from the fuel consumption per car-km. These levy effects are calculated for each of the two cases for the year of 2040 (Present Value). More detailed explanation of this change is presented in Table D-15 in Appendix D.2.

#### 4.3.5 Missing criteria

Although the criteria defined for this CBA are trying to cover a lot of different perspectives and aspects for the introduction of the automated vehicles into the network, still there are criteria that are missing. This is because of mainly two reasons: a) difficulty in defining monetary values on every possible criterion and b) non availability of data for the new mode. Thus, the possible criteria for the CBA are:

- ➤ Safety
- > Noise
- > Comfort
- Operational Reliability (although the reliability is reflected into the case study through the speed factor (chapter 3.5.6), though, this is not directly presented in the CBA as a separate criterion)

All the above could be further examined by other researchers in the future. However, for the purposes of this research, it is assumed that the most important aspects are already captured by the evaluation criteria described in chapter 4.3.4 and the missing criteria could not change significantly the outcomes of the CBA.

#### 4.3.6 Outcomes of CBA

After the specification of the 5 perspectives/stakeholders involved into the new system and the total 14 evaluation criteria associated with these perspectives, together with their calculated input data for the CBA (Appendix D.2), the final stage includes the execution of the CBA for each of the two cases. However, before presenting the outcomes of the CBA, it is essential to define the basic output values that are used in the CBA evaluation process:

- $\succ$   $\Delta$  is the value of each criterion that represents the difference (effects) between the reference case (without the automated vehicles) and each of the cases (after the implementation of the automated vehicles) for the year of 2040 (the time horizon of the CBA).
- Present Value is defined as the monetary translation of the above mentioned difference (effect) for the same time horizon.
- > **Total Benefits** are the sum of the positive Present Values of the respective criteria.
- > **Total Costs** are the sum of the negative Present Values of the respective criteria.
- > **Net Present Value** is the summation of the total benefits and the total costs.

The CBA conducted, based on all the above and by implementing the interest rate of 5,5 % for the 30 year time horizon of the CBA, is presented in Table 4-3.

#### Table 4-3: System's CBA for cases 1 and 2

Dorsportivos	Critoria	Case 1: Bus Line	Based AV Route	Case 2: Shortest Path Based AV Route		
Perspectives	Criteria	Δ	Present Value (€ * 10 <sup>6</sup> )	Δ	Present Value (€ * 10 <sup>6</sup> )	
	Investment Effects					
AV Operator	Construction costs of new AV stops	-2	-2	-3	-3	
AV Operator	Purchase of the automated vehicles	-0	-0	-0	-0	
	<u>Fare Effects</u>					
Passengers	Passenger (fare) effects for BTM switchers (# of passengers * km * $10^6$ )	+4	+0	+8	+1	
Passengers	Passenger (fare) effects for Car switchers (# of car*km * I/km*10 <sup>6</sup> )	+1	+0	+2	+0	
Passengers	Passenger (fare) effects of automated vehicles (Excluding BTM and Car Passengers Switched) (# of passengers * km * 10 <sup>6</sup> )	-5	-1	-3	-0	
AV Operator	AV operator (fare) effects from AV users (All Users) (# of passengers * km * $10^6$ )	+8	+1	+4	+1	
BTM Operator	BTM (fare) effects for operator (# of passengers * km * $10^6$ )	-5	-1	-8	-2	
	Externality Effects					

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Society	AV Externality Effects	-0	-0	-0	-0
Society	Car Externality Effects (# of car-km $*$ 10 <sup>6</sup> )	+13	+19	+18	+26
	<b>Operational Cost Effects</b>				
AV Operator	AV operational and maintenance costs	-12	-12	-11	-11
	<u>Levy Effects</u>				
Government	Levy Effects	-13	-0	-18	-0
	Travel Time Effects				
Passengers	BTM in vehicle travel time effects (h $*$ 10 <sup>6</sup> )	+7	+7	+13	+13
Passengers	BTM waiting travel time effects (h $^{*}$ 10 <sup>6</sup> )	-8	-8	+20	+20
Passengers	Car in vehicle travel time effects (h * $10^6$ )	0	0	0	0
Total Benefits (€ * 10 <sup>6</sup> )			+27		+61
Total Costs (€ * 10 <sup>6</sup> )			-24		-16
Net Present Value (€ * 10 <sup>6</sup> )			+3		+45

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According to the outcomes of the CBA, the Net Present Value for both cases is positive: +3 €millions for case 1 and +45 €millions for case 2. For both cases, the highest benefits are coming from two important sources:

- Car externality effects: The car volumes-km that decreased in both cases after the implementation of the automated vehicles (13 million car-km less in case 1 and 18 million car-km less in case 2 in 30 years), have significant benefits for the society in terms of monetary externality effects. For case 1, the benefits, derived from the decrease of car-km, are equal to + 19 €millions and for case 2 equal to +26 €millions.
- ► <u>BTM in-vehicle travel time effects:</u> For both cases, the benefits for the users that remain to the BTM network, in terms of in-vehicle travel time, are quite notable. The monetary in-vehicle travel time effects for BTM users in case 1 are equal to +7 €millions, while for case 2 equal to +13 €millions.

These two main beneficial impacts have both contributed to the positive Net Present Value of the new mode system in both cases. Though, the implementation of the automated vehicles is connected to significant costs in both cases:

AV operational and maintenance costs: These inevitable costs for both cases are the main sources of cost effects. For case 1, the O&M connected to the operation of the AV system are up to -12 €millions and for case 2 equal to -11 €millions.

Although both cases are positive in terms of Net Present Values (+3 and +45 €millions for case 1 and 2 respectively), the second case is significantly more beneficial than the first case. The reason for this notable difference is multiple:

- Lead in car externality and BTM in-vehicle travel time benefits for case 2: Both cases are having high benefits in terms of car externality effects and BTM in-vehicle travel times, however the Present Values for case 2 are higher, compared to case 1. This difference for both criteria in favour to case 2 (+7 €millions difference between case 2 and 1 for the car externality effects criterion and +6 €millions difference for the BTM in-vehicle travel time effects criterion) has generated a total boost of +13 €millions for case 2, compared to case 1.
- Opposite BTM waiting time effects between case 1 and 2: Distinguishable is the fact that the waiting time effects for the users remaining to the BTM network are very positive in case 2 (+20 €millions), while in case 1 they are considerably negative (-8 €millions). These opposite effects are growing even more the difference of the Net Present Values of cases 1 and 2, in favour to case 2.

An explanation for the waiting time effects to be negative in case 1 and very different in absolute values from case 1 (28 €millions difference) is the usage of high penalties in the bus stops for BTM and AV lines. During the modelling part of both cases, and especially the determination of the penalties per bus stop (chapter 3.5.6), it is pre-defined that the penalties for transfers between BTM and AV users are very high, so that the automated vehicles are strictly oriented as access/egress trips for train trips.

On one hand, the number of bus stops used simultaneously by the BTM and AV transit lines is higher in case 1 than in case 2, so more stops used by BTM and AV users are having high penalties for transfers in case 1. Passengers of BTM lines in case 1 that still choose the AV lines for their last-mile journey, are facing the consequence of having high transfer penalties, depicted to the expected waiting times that passengers have in the respective BTM/AV stops. On the other hand, the AV stops of case 2 are mostly dedicated to the AV line and only few are used simultaneously by BTM and AV transit lines. So, the respective penalties and waiting times per BTM stop used by both mode systems are affecting far less BTM passengers, compared to case 1. Thus, summarising all the above, case 1 has negative waiting time effects, while case 2 is having positive effects.

### 4.4 Conclusions and Recommendations

In summary, chapter 4 is elaborating on Part C of the methodology, namely the evaluation of the chosen 2 cases that derived from the application of Parts A and B of the methodology in the case study of chapter 3. Thus, this chapter has defined the most important outcomes of both cases, in respect to demand related results and CBA results. The entire evaluation has revealed two important and contradicting outcomes:

- The results related to the pure demand of the automated vehicles (AV users, train users, access/egress mode choices from Veenendaal Centrum and zones' modal split) have defined a small advantage over the first route case for all criteria besides the zones' modal split, in which the second case is leading over the first case.
- Based on the outcomes of the CBA, both cases are beneficial (Net Present Value of +3) €millions for case 1 and +45 €millions for case 2). However, the CBA outcomes that incorporated some of the above results as input data for the evaluation, have favoured by far the second route case in terms of the Net Present Value.

Based on the above two points, although the demand-related criteria are providing a slight lead to case 1 in total, the CBA evaluation has switched the results in favour to case 2. This proves that the application of the demand-related criteria to both cases is providing important results, still the CBA is a tool that investigates broader aspects, and thus, better overview of the monetary effects of the new mode. In conclusion, taking into consideration both the AV potential demand related results and the CBA, the answer is not straight forward regarding the best case, since the results are contradictive.

A crucial fact generated through this project is the reliability and the high accuracy offered by the model used. It is important to assure every time that the used model is examined and tested for realistic (as possible) results, so that the outcomes are not deviating much from reality. Moreover, the cost facts used for the automated vehicles are based on two aspects that could be reversible in the future:

The financial data are based on the current technological development of the automated vehicles. This means that future improvements could generate far less costs for the automated vehicles than the ones used in this CBA (especially O&M costs).

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The costs are referred to a single case study and not taking into account aspects such as economies of scale for wider operation of the automated vehicles into the network system. In this latter case, the costs related to the automated vehicles, especially the operational and maintenance costs could be significantly reduced.

So, by taking these two economic aspects into account, the CBA could result in more positive results for both cases than the current outcomes. This is an investigation that requires future research. Moreover, taking a broader look on the evaluation process conducted in chapter 4, the points that request further investigation in the future are summarised below:

- In chapter 2.5 it is discussed that the methodology is not incorporating in the CBA the total travel time effects that the AV users receive, compared to the total travel time effects of the BTM and car users. This aspect could be elaborated by a future study, in order to define the potential costs or benefits for the AV users.
- As mentioned in chapter 4.3.5, there are certain criteria that are not used in the evaluation process (noise, comfort etc.), constraint mostly by the abilities of the model or the available data. A future research could incorporate these criteria into the evaluation process and determine the level of influence to the final results with and without the use of these criteria.
- For the CBA, the demand for all modes, including the automated vehicles, is assumed to be constant per year. A future investigation could be realised in order to predict the potential AV demand for the time horizon of the CBA in more precise values and determine in this way the accurate AV demand of the future.

## **5 CONCLUSIONS AND RECOMMENDATIONS**

The final part of this research is presenting the main conclusions, regarding the total of the project (chapter 5.1), and relevant recommendations for future scientific and practical studies (chapter 5.2).

#### 5.1 Conclusions

This project answers the main research question, presented below:

# What methodology can be developed for the systematic scanning and evaluation of areas in order to identify potential for fully automated vehicles as egress/access modes for low/medium demand train stations?

Based on this research question, a methodology is developed, as illustrated in Figure 5.1. This methodology is examining the potential of successfully implementing the automated vehicles into a regional setting in terms of demand and cost-benefit ratio. Taking into consideration this goal, the methodology developed is a stepwise approach, structured in three main parts: identification/design process, determination of cases and evaluation process. The main conclusions for each of these parts are presented below.

#### Methodology-PART A: Identification/Design Process

PART A of the methodology is consisted of three levels: train station, zone and route level. In the first two levels, an identification process is involved for finding the highest potential train station and its associated zones, in order to implement the automated vehicles as an access/egress mode for train trips. The third level is a design process for the potential routes that the automated vehicles would operate on. Zooming into each level:

For the train station level, the objective is to find the highest potential train station within a chosen area, based on 3 identification criteria: 1) daily train trips per train station, 2) access/egress mode demand per train station and 3) maximum potential zones associated. The last criterion is a zone-oriented criterion, which is satisfied via 5 constraints, applied to each associated zone of the investigated train stations: 1) mode/purpose demand, 2) association of zones only to one train station, 3) location of zones from train stations further than walking/cycling distance, 4) daily bus service level and 5) maximum number of potential zones. The application of the 3 criteria is

an exclusion process, so that the train stations are filtered out for each criterion and the highest potential train station is eventually chosen.

- > For the **zone level**, the objective is to find the highest potential zones, associated to the train station chosen in the previous level, according to 5 identification criteria: 1) daily trip volumes, 2) total bicycle share, 3) bicycle share for work/business purposes, 4) bicycle share, compared to car and PT share and 5) bicycle share for work/business purposes, compared to car and PT share for the same purposes. These criteria are applied simultaneously and the zones are evaluated, in order to define their ranking. The ranking of the zones is used as input information for PART B of the methodology.
- For the route level, the objective is to design the highest potential route that connects the chosen train station with the chosen zones. The design is accomplished via 5 criteria, applied simultaneously: 1) capture of maximum demand, 2) attractive travel distances, 3) congestion levels, 4) operational speed and 5) allowance of motorised modes. The potential routes derived after the application of the 5 criteria are further used as input for PART B of the methodology.
- In the zone level, a sensitivity analysis is performed, as well as a validation associated to both train station and zone level.

#### Methodology-PART B: Determination of Cases

In PART B, different cases are determined, namely potential combinations of train stationzones-routes that the automated vehicles would serve. The choice of the highest potential train station is fixed and established already in the train station identification level of PART A. However, the choice of zones and routes is dependent on: 1) the number of zones chosen (based on their ranking in the zone identification level of PART A), 2) special network aspects and 3) operational characteristics of existing network. So, in this part, different train stationzones-routes cases are created, which are further evaluated in PART C.

#### Methodology-PART C: Evaluation Process

The final part of the methodology is evaluating the cases derived from PART B, based on two sets of criteria: 1) demand-related criteria and 2) cost-benefit analysis criteria. The first set involves 4 different demand aspects that are examined per case: a) AV users, b) train users, c) access/egress mode users from/to the chosen train station and d) modal split of each chosen zone. The second set incorporates systematic criteria for six main effect areas (investment, fares, travel times, operational and maintenance costs, externalities and levy), all associated to 5 different perspectives of the system affected, namely the passengers, the AV and BTM operators, the society and the government. The outcomes per case are translated into monetary values for each costs-benefit criterion in a CBA framework, which is used as an evaluation tool for the potential cases examined. The purpose of this part is to define, quantitatively, the effects of the implementation of the automated vehicles, in terms of demand and costs-benefits, for each case.



Figure 5.1: Methodology

The methodology developed is further applied to the province of Utrecht in the Netherlands, the main conclusions of which are summarised below.

#### **Application of Methodology-PART A: Identification/Design Process**

PART A is applied into the case study, and the main outcomes are:

- The application of the train station identification level revealed Veenendaal Centrum as the highest potential train station for implementing the automated vehicles. Regarding the zone identification level, the ranking process designated 4 highest potential zones, while in relation to the route design level, two route scenarios are pre-determined: current bus line route scenario and shortest path route scenario. Moreover, one route option per scenario is determined in the network.
- The sensitivity analysis and the validation justified the choice of Veenendaal Centrum and the 4 highest potential zones.

#### **Application of Methodology-PART B: Determination of Cases**

PART B is applied simultaneously with PART A in order to decrease the number of possible options, due to time limitations. So, only two cases are further evaluated in PART C:

- Case 1 Current Bus Line Based: In this case, the automated vehicles are implemented as access/egress mode choice for Veenendaal Centrum and the 4 zones chosen, by operating on a route that is following the bus lines (with the respective bus stops) that currently serve the chosen train station and zones.
- Case 2 Shortest Path Based: This case is using the automated vehicles as access/egress mode choice for Veenendaal Centrum and the 4 selected zones in a route that would serve them with the shortest travel distance in total.

#### **Application of Methodology-PART C: Evaluation Process**

The final part of the methodology is applied for both cases derived from Parts A and B. Starting with the first set of evaluation criteria (demand-related criteria), the main conclusions are summarised below:

The number of total AV users per day is 600 approximately passengers for the current bus line based case and approximately 500 passengers for the shortest path based case (Figure 5.2). Possible explanation for this difference is the number of existing bus stops in the first case, capturing already existing demand



Figure 5.2: Total AV passengers per case per day (both directions)

per bus stop, compared to the second case, where fewer existing bus stops are used. This means that the higher connectivity offered in the first case, outweighs the low travel distance offered in the second case. Moreover, the AV users boarding/alighting in the stop outside the train station of Veenendaal Centrum per day are approximately 300 passengers for the current bus line based case and approximately 200 for the shortest path based case. This difference might be associated again to the connectivity advantage offered in the first case, compared to the second case.



Figure 5.3: Train user changes for case 1 and 2 in train station Veenendaal Centrum

The number of train users in Veenendaal Centrum have increased by approximately 20 passengers per day for the current bus line based case and decreased by approximately 40 passengers per day for the shortest path based case (Figure 5.3). This could be explained by the fact that the second case is "avoiding" currently used bus stops, and thus, restraining the

former BTM users to switch to the new mode. So, the higher connectivity offered in the first case might be the reason for higher access/egress mode trips from Veenendaal Centrum, compared to the second case.

The access/egress mode users outside the train station of Veenendaal Centrum switched to the automated vehicles with higher volumes (29 access/egress passengers for automated vehicles per day) in the first case than in the second (only 6 access/egress passengers for automated vehicles per day). For the first case, the demand for automated vehicles as access/egress mode outside the train station is coming from former BTM users mostly, while for the second case, by both BTM and

bicycle shifts. These volume changes are in line with the respective changes in train trip volumes for cases 1 and 2.

In respect to the modal split changes per zone in each case, it has slightly changed for both cases and for every zone examined, in favour of the public transport (in which the automated vehicles are incorporated). The increase of the PT percentage has derived from both the car and the bicycle. Moreover, the positive changes of PT for all zones are between 0,18-0,45% for the first case and for the second between 0,22-0,55%. These changes are very small, though it is justified by the fact that the routes served by the automated vehicles are dedicated only to 4 zones and the train station of Veenendaal Centrum, while these modal splits refer to the entire O-D matrix of each zone.

The second set of evaluation criteria are incorporated into a systematic CBA, for which the main conclusions are presented below:

- The CBA performed for each of the two cases revealed that both cases are having a positive Net Present Value (NPV). The NPV of the first case is close to the break-even value (+ 3 €millions), while the NPV of the second case is considerably high (+ 45 €millions).
- The benefits after the implementation of the automated vehicles into the existing network for both cases derive from two main effect areas. Firstly, from the positive car externality effects (+ 19 €millions for the first case and + 26 €millions for the second). And secondly, from the in-vehicle travel time effects on the BTM users (+ 7 €millions for the first case and + 13 €millions for the second).
- The main costs in both cases are coming from the operational and maintenance costs of the automated vehicles (-12 €millions for the first case and -11 €millions for the second).
- The difference of the NPV between the first and second case derives a) from the higher benefits (car externality effects and in-vehicle travel time effects for BTM users), in terms of actual values, for the second case, compared to the first one and b) from the positive effects on waiting travel times for BTM users in the second case (+20 €millions), compared to the negative effects on waiting times of BTM users for the first case (-8 €millions). Possible explanation for the latter opposite values is the usage of high penalties per bus stop for transfers between BTM and AV transit lines, as chosen in the modelling process for dedicated service between automated vehicles and train service only.

In total, the evaluation has revealed that, although the first case is scoring slightly better in terms of pure demand-related criteria, the second case is scoring far more positive in the CBA. So, the answer is not straight forward regarding the best choice. In conclusion, automated vehicles could become a viable solution, not only in terms of demand, but also, in terms of costs-benefits ratio.

Regarding the modelling of the automated vehicles into the OmniTRANS model of Utrecht, the main conclusions are:

- The usage of the detailed model of Utrecht, in terms of access/egress mode choices, is providing useful information for all possible access-main trip-egress trip combinations, and thus, more insight for the automated vehicles as well, in respect to train trips.
- The automated vehicles, for reasons of simplicity and time limitations, are modelled as part of the main PT mode choice and constraint through penalties into an access/egress mode choice for train trips.
- The Value of Time (VoT), as well as the disutility functions for the distribution/modal split and assignment steps are the same as the BTM network. The reason for this choice is binary: a) the model of OmniTRANS is providing simplistic options in terms of coefficients' values and number of variables and b) the automated vehicles do not differ significantly from the BTM system (main difference is on the driverless operation of the AVs compared to the BTM). Expected operational unreliability of the new mode is incorporated into the speed of the automated vehicles, with the application of a lower speed factor. Nevertheless, issues, such as feeling of on-board security, as perceived by AV passengers, noise or comfort are not incorporated into the model, due to lack of data and restrictive options available from the model.
- The automated vehicles' schedule is modelled in a way to reflect the expected synchronization between automated vehicles and trains in Veenendaal Centrum.
- $\succ$  The fare system of the automated vehicles is lowered by 55% per km, than the respective fare system of the BTM. This choice reflects the operational cost savings of the automated vehicles in terms of drivers' salaries and fuel consumption.
- > The number of vehicles required per case is 4, so that the operation of the new system is accomplished in synchronization with the train services per day.

#### 5.2 Recommendations

The methodology and its application in this project reveal the highest potential train stationzones-routes combinations for successfully implementing the automated vehicles as access/egress mode choice for low/medium demand train stations. However, further investigation is required from both scientific and practical perspective. The recommendations related to both aspects are presented in the following parts.

#### 5.2.1 Future scientific recommendations

The methodology in PART A used a set of identification/design criteria for each of the three levels examined. Though, additional identification/design criteria/aspects could highlight more the beneficial input of the automated vehicles to the system. These aspects are for example special population groups (older people, children or people with physical inabilities), regional settings with high emission rates or areas with spatial changes such as new residential areas for families or shopping malls. All these examples are perspectives in which the automated vehicles could be used as potential mode choice, and not examined in this research.

Furthermore, the methodology is having as basic prerequisites the focus on low/medium demand train stations and the incorporation of the automated vehicles as access/egress mode for train trips into the network. However, these two constraints could be altered in PART A by a future research. Firstly, the potential for implementing automated vehicles to all possible train stations could be examined, and not only focus on the low/medium demand ones. Secondly, the implementation of automated vehicles as access/egress mode for train trips could be developed in a more general framework. This means, alterations in the identification/design part of the methodology (train station, zones and routes levels) could be applied so that the automated vehicles are investigated as a) access/egress modes for every PT or car trips, and not only for train trips or b) identify the potential of automated vehicles as main mode.

Regarding the evaluation part of the methodology, and more specifically the CBA, two additional elements could provide better insight of the effects that the automated vehicles have in the associated system. The first refers to the total travel time effects (in-vehicle and waiting time effects) of the automated vehicles in comparison to the travel times of other modes (especially PT and car). The second refers to the incorporation of effects associated to other modes (besides the BTM and car) into the evaluation process of the CBA.

For the model set up for both cases, a lot of simplifications and assumptions are made, because of lack of data and limited abilities of the model. The lack of data is mostly related to the fact that the operational framework of the automated vehicles is a new concept, with limited investigations upon this topic. So, some of the points that would request future investigation are the influence of different aspects upon the disutility functions of the new mode. For instance, the relationship between the passengers' feeling of security when using the automated vehicles and their final mode choice is a point that is not examined yet, and thus, not incorporated in this project. Moreover, aspects such as the comfort offered by these modes, the level of operational reliability or even the possibility of using a different VoT for automated vehicles than the one from the BTM mode used in this project, require further investigation. In this way, the sensitivity of passenger's mode choice is examined.

In this project, a major simplification is applied, namely no replacement of any mode is realised in both cases developed for the automated vehicles. This means that the car, bicycle, pedestrians and PT network remain as in the current situation. This latter point highlights the fact that this project has not investigated the potential of replacing an existing mode, and especially the current bus lines that operate around the network examined in this case study. This generates new opportunities for future researchers:

- Development of a methodology that identifies potential bus lines that could be replaced by automated vehicles, with special focus on the low demand bus lines. Criteria such as the on-board passengers per bus line, the frequencies, the boarding/alighting volumes per bus stop and the regional setting of operation (rural area or city) could be used as input for the methodology.
- Modelling of the automated vehicles as replacements of existing bus lines, in addition to their new dedicated routes, as determined by the methodology developed here.

Examination of the potential "reaction" of the transport network, in terms of demand and costs-benefits, after the replacement of existing bus lines by automated vehicles.

In total, the methodology developed in this research could become a useful tool for researchers to investigate the potential of implementing automated vehicles in a regional setting. The idea behind this methodology is to capture important aspects (spatial, operational, demand-related aspects and costs-benefits), which are necessary for the investigation of the potential of automated vehicles, either investigating them as an access/egress mode for any main trip or as main mode itself. So, this methodology, with respective adjustments, could support the investigation of the potential of automated vehicles in general.

#### 5.2.2 Future recommendations for practical cases

The cases generated for the purposes of this project are only 2 (current bus line based and shortest path based). Though, more cases involving different number of potential zones per case or cases that include route options that operate through city centres or highways could be examined by future researchers/modellers/policy makers. In this way, different network aspects could be captured, and so, the determination of the maximum possible potential zones and routes out of a wider set of potential options (optimal network design).

During the validation process, although Veenendaal Centrum and its respective zones are revealed as highly potential candidates, also other zones and respective train stations appeared as more interesting options (e.g. Abcoude, Veenendaal De Klomp and Den Dolder train stations with their highly potential zones). Thus, a future research could examine all these choices as well and compare the outcomes of each case study with the one in Veenendaal Centrum in terms of demand and CBA ratio.

In this project, the modelling of the automated vehicles is realised as part of the main PT mode choice, and then constrained as an access/egress mode for train trips, and not as an access/egress mode from the start. However, the modelling of the automated vehicles as access/egress mode choice would provide data that are not captured by this model set up. For instance a) the modal split of all access/egress mode choices for train trips could be determined, including also the automated vehicles as access/egress mode, b) the total volumes of train users that switch to automated vehicles would be more distinctive, c) the accurate determination of the car and bicycle users switched to PT as main mode choice and the percentage of those that switched to automated vehicles as access/egress mode choice.

Moreover, the use of more "detailed" coefficients in the OmniTRANS model that could capture more precisely the effect of each variable used on the disutility functions, and thus, on the distribution/modal split and assignment choices, is a point that requests further investigation and data. The availability of more sophisticated coefficients per variable, especially for the total travel time and fare variables would determine the mode choice in a more accurate way, by taking into account the sensitivity of passengers over each mode per variable.

Furthermore, the use of vehicle specifications that are not based on the available technology is applied in this project. Although the entire project is not constrained by the current technologies, still the vehicle specifications are based on an existing automated vehicle structure, namely the vehicle ULTra. This vehicle structure limits the potential abilities of the new mode to specific speed abilities (maximum 50 km/h) or capacity limitations (maximum 20 passengers). Future research could be developed to determine different technological abilities for the automated vehicles, and thus, test how the vehicle specifications affect the final outcome and in which level.

In addition, the costs are referred to a single case study and not taking into account aspects such as a) economies of scale for wider operation of the automated vehicles into the network system and b) that the demand is not constant per year (as assumed in this project). In the first case, the costs related to the automated vehicles, especially the operational and maintenance costs could be significantly reduced, while in the second, demand changes per year could reflect better the actual trend of AV users in the future.

Finally, the automated vehicles in this project are implemented without examining the potential of replacing existing bus lines. The concept of the automated vehicles is, besides others, to provide alternative options for existing networks. Thus, the examination of replacing current bus lines, especially the ones with low demand in regional areas of the Netherlands, with this methodology (incorporating necessary alterations to the methodology and the model) could be used as a tool for bus operators or policy makers to determine a) the potential demand changes between the operation of a regular BTM system and the automated vehicles and b) the potential costs-benefits changes before and after the replacement of BTM lines by automated vehicles.

In conclusion, although further adjustments and investigations are required, this methodology could be used as a tool for identifying the potential for automated vehicles as access/egress mode choice for train trips, both in terms of demand and cost-benefit ratio. This methodology is easily implemented by both scientific and practical purposes. Taking a step further, this methodology could be used as guidance for policy makers to investigate the potential of using the automated vehicles as an access/egress mode choice for any other main PT mode as well, but also, using the automated vehicles as main trip choice in general (with necessary alterations of the methodology). This latter could become successful when combined with replacements of existing bus lines instead of simultaneous operation, so that the two systems are not overlapped and the outcomes degraded.



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## A. APPENDIX Familiarization with automated vehicles

This Appendix provides important information regarding the automated vehicles. The fields elaborated in this Appendix refer to the benefits and costs associated to automated vehicles, the definition of the levels of automation of vehicles, the technologies involved, the categorization of the automated vehicles, and finally, the technical characteristics of automated vehicles, based on certain case studies. All these points are further described in the following parts.

#### A.1 Benefits and Costs of the Automated Vehicles

The impact areas that automated vehicles influence positively are the mobility in general and the traffic efficiency (in terms of time savings, congestion and capacity), environmental sustainability and road safety, regarding the driving perspective and the elimination of accidents caused by human factors (Meyer, 2014). SMART (2011), iMobility (2013) and Varotto, et al. (2014) are elaborating further on the road safety aspect by establishing the opinion that high or full automation will contribute positively to the safety through the reduction of human mistakes during driving and the general alleviation of congestion in both urban areas and motorways, by generating more improved driving styles, reduced headways and fewer speed fluctuations (see research of Kang (2000) for more details regarding the time losses during accelerations/decelerations).

A key advantage of the automated vehicle concept, compared to the regular modes and especially buses, is that these vehicles are in general driverless and electric engine operating vehicles. These two costs are actually the main source of expenses for the bus operators. According to Connexxion (2015), the Dutch regional bus operator, the highest costs are captured by the driver and fuel cost percentages (regarding the direct variable costs). These costs consist of a total of 70% out of the total operational costs of the bus system, costs that with the use of automated vehicles can be eliminated.

The main costs for implementing the automated personal modes (and projected generally to the automated vehicles) are divided in three parts, namely the infrastructure, the control system and the vehicle itself (Kerr, et al., 2005). More specifically, the detailed cost breakdown revealed the following components involved: guideway, stations, maintenance and support capabilities, power and utility, vehicles, command, control and communication, and finally the engineering and project management.

From the survey of Kerr, et al., (2005) it appeared that the infrastructure costs (guideway, stations, and maintenance and support capabilities), namely the capital costs for implementing the automated vehicles in terms of infrastructure, are representing the 42.8% of the total investment costs. However, the same, more or less, infrastructure investment costs are related to the regular bus systems. The difference is reflected in the control systems (costs that are associated mostly with the automated vehicles) and the vehicles, where automated vehicles are having higher acquisition cost than the regular buses. The latter is more detailed discussed in the research of Greenstone & Looney (2012), where a comparison has been performed among different energy sourced vehicles, revealing different capital costs in terms of acquisition costs for the electric vehicles are high (compared to the rest), but these vehicles have the lowest fuel costs. The above comparisons are shown in Figure A.1.



Figure A.1: Private and external cost distribution of different energy resources (Source: Greenstone & Looney, (2012))

Moreover, in the study of Peng, et al. (1999), the outcome of their research proved that the benefits for the user are the highest among the total benefits of the automated vehicles (Figure A.2). Young, et al. (2009), in a rough investigation they performed, concluded that the annual capital investment for a PRT system, with a timeline of 10 years, is approximately €19.6 M and the operational costs €16.9 M, which decrease as the years pass by.



Figure A.2: Distribution of benefits of automated vehicles (Source: Peng, et al., (1999))

Finally, in the research of May, et al. (2012), the implementation and operating costs of cybercar feeder and PRT in 4 different cities are investigated. The general outcome is that both vehicle types performed well in terms of financial return and Benefit-Cost Ratio.

### A.2 Definition of Automation Levels

According to NHTSA (2013), the main levels of automation are 5, namely:

#### Level 0 (No-Automation):

Driver is in complete and sole fundamental control of the primary vehicle controls at all times (brake, steering, throttle, motive power)

#### Level 1 (Function-specific Automation):

- Driver has overall control
- Involves one or more specific control functions
- > If multiple functions are automated, they operate independently from each other
- Driver can choose to cede limited authority over primary control (as in adaptive cruise control)

#### Level 2 (Combined Function Automation):

- Shared authority
- Automation of at least two primary control functions
  - Example: adaptive cruise control used in combination with lane centring
- Driver cedes active primary control but, responsible for monitoring and safe operation
- Driver expected to be available at all times
  - Note: With no advanced warning driver can relinquish control

#### Level 3 (Conditionally "Autonomous"):

- Driver can cede full control authority under certain traffic and environmental conditions.
- > Driver expected to be available for occasional control.
- Designed so driver is not expected to constantly monitor roadway.

#### Level 4 (Fully "Autonomous"):

- Human provides destination or navigational input, but is not expected to be available for control.
- Responsibility for safe operation rests solely on the autonomous systems.

SAE (2014) is upgrading the abovementioned levels by diversifying Level 4 into two separate levels, namely the high and full automation, both explained in detail below:

#### Level 4 (High automation):

The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene

#### Level 5 (Full automation):

> The full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver.

#### A.3 Technologies Involved in Automated Transport Systems

The holistic operation of the automated vehicles is directly connected to the technologies that enable vehicles to communicate with each other (V2V) and with the infrastructure (V2I) in order to prevent disruptions and incidents (Zhang Y., 2013). These communication systems are futuristic, state-of-the-art, technologies that embrace the automated vehicles in such a way that would assure their smooth operation without problems, not merely the vehicles, but more importantly the surrounded (traffic) environment.

Zhang (2013) presented the research of Lukuc (2012) regarding some of the technologies that are connected to both V2V and V2I communication systems. According to his research, there are three main applications important for this purpose: 1) the forward collision warnings that could be based on either V2V or V2I communication systems and are responsible for alerting the vehicles for collision dangers, 2) the blind spot/lane change warnings (again applicable to both vehicles and infrastructure) that is related to the warn from side-to-side beyond a set threshold, and finally, 3) the left-turn assists, which are infrastructure-assisted functions and are connected with the information of the intersection traffic signals in order for the vehicles to cross the intersection.

Regarding the V2V and V2I communication systems, Gasser & Westhoff (2012) and SMART (2011), point out the significance of the ADAS systems towards the enhancement of these information systems. Apparently, in the SMART project (2011) the close relationship is recognized, that the ADAS systems have, with V2x communication systems, suggesting that the automation of the first and the improvement of the information systems of the second will eventually converge to the same path and be considered as one in the future. It is concluded that "the reliability of the ADAS-based automated driving and of the V2V- and V2Ibased cooperative driving plays an important role in all discussions with manufacturers and legislators...Existing applications of V2I are based on GPS, Mobile Phone Signals and ANPR", proving the importance of the ADAS systems to the V2V and V2I applications.

Another approach, regarding the technologies involved, is the aspect in which the technologies are to be examined, namely driver centric, network centric and vehicle centric (Guzman, et al., 2012). Driver centric systems are aiming in improving the situational awareness of the drivers through driving assistance systems used during drivers' decision making. The network centric systems use wireless networks that assure the sharing of information between vehicles and infrastructure. Finally, the vehicle centric systems are aiming to convert the vehicles into fully autonomous vehicles, which means that the driver is no longer responsible for the control of the vehicle. The respective technologies and applications for all three perspectives are creating the necessary technological framework in order for the automated vehicles to feasibly and effectively operate on the transport networks.

### A.4 Automated Vehicle Categories

The first categories of automated vehicles are described by USCommitte (1975). The characteristics of each category are in detail presented below:

- Shuttle-Loop Transit (SLT): This category is the simplest of all AGT systems. The shuttle transit is using a single pathway with or without intermediate stops and few or no switches. Also, the loop transit is moving along a closed path with random stops along. The size of both types can vary, whereas both may travel singly or coupled together with trains.
- Group Rapid Transit (GRT): This type of service systems serve groups of people that have the same or similar origins and destinations. GRT is considered to have shorter headways and more switches along its route. Moreover, GRT systems have dedicated stops along the guideways that are sided off in order to not intervene with the regular traffic. Finally, the capacity of these vehicles can vary between 10 to 50 people, whereas their headways range from 3 to 60 seconds.
- Personal Rapid Transit (PRT): The last category has features similar to a taxi operation, since it is used by 1 person or groups of up to 6 people travelling together by choice. These vehicles can travel to off-line stations that are then connected to a guideway network. Moreover, this category includes a lot of switching in order to follow the shortest possible path without intermediate stops. In conclusion, in this category, the headways of the vehicles can potentially be 3 seconds or less.

Though, May, et al. (2012) and Alessandrini, et al. (2014) upgraded the above categories, adjusting them to new technological improvements and developments. The new categories identified by these researchers are:

- Personal Rapid Transit (PRT): Individual transport systems that usually use 4-place vehicles running in dedicated lanes. PRT is operating as a taxi service, carrying passengers from origin to destination without intermediate stops. Their maximum speed can reach up to 40 km/h.
- CyberCars (CC): Road vehicles (similar to the ParkShuttle in Rotterdam), operating in segregated, or not, lanes and having an average capacity of 4 to 20 passengers. The vehicles of this category are working as collective taxis, in which the passengers can

have different origins and destinations, however their service is scheduled, rather than on demand. Finally, the maximum speed of this system can be up to 25 km/h.

- High Tech Buses (HTB): Vehicles for mass transport that is using exclusive infrastructure for buses or shared operation with the rest of the road traffic users. The routes served by these systems could connect the suburbs with the city centre, while there is at least one route that is connecting the city centre with a major facility such as shopping centres or airports.
- Dual-Mode Vehicles (DMV): Finally, the city vehicles have zero or ultra-low emission and a lot of additional automated control systems such as driver assistance, parking assistance, collision avoidance, as well as supporting full automated driving in certain circumstances, such as platooning for relocation.

#### A.5 Technical Characteristics of Automated Vehicles

An important aspect in all case studies that have introduced the automated vehicles to public is the determination of the technical characteristics of these vehicles, namely the speed, the expected waiting time, number of stops and everything that is related to the operation of these modes to the public transport network. This part is aiming in pointing out the main technical characteristics of some case studies in order to understand the operational performance of the automated vehicles, given the current technology. The choice of these characteristics in each case study is based on their technical abilities, the performance and demand expectations of policy, public, operators and manufacturers, the existing network and its facilities, and finally, the structure of the region/town/city served.

Starting with the Netherlands, the most long-term operating systems are the ones in Business Park Rivium in Rotterdam (which is still operating as public transportation mode to business park) and in Schiphol airport of Amsterdam (not in operation since 2004 and used to be the connector to and from the parking lot of the airport). Both systems used ParkShuttle vehicles (Table A-1 and Table A-2).

Description	Public Transportation to business park				
Operational period	Phase I: February 1999 – November 2001				
	Phase II: December 2005 - present				
Patronage	1.500 passengers (daily)				
Peak Capacity	500 p/ph/pd				
Service Frequency	2.5 minutes (peak hours)				
Service Frequency	On-demand (off-peak hours)				
Times of Operation	12hrs. p/d, 5 days p/w				
Configuration	Line-connection				
Operations	On-schedule / on-demand				
Connections	Ride sharing, Multiple Origins to Multiple Destinations				
Type of vehicle	2 <sup>nd</sup> generation ParkShuttle				
Number of Vehicles	6				
Passengers seated/standing	12 / 10				

Table A-1: Technical characteristics of the Business Park Rivium Application. (Retrieved from ParkShuttle Update (2015))

Drive	Electric
Supervisory Control System	SuperFrog
Track Length	1800 meters
Number of Stations	5, on-line
Berths per station	3 stations with 2 berths, 2 single berth stations
Crossings for Traffic/Pedestrians	6 (3 at grade) / 5 (all at-grade)

 Table A-2: Technical characteristics of the Amsterdam Airport Schiphol Application. (Retrieved from ParkShuttle Update, 2015))

Description	Parking lot connection				
Operational period	1997 –2004				
(Estimated) Patronage	>2.500.000 passengers				
Peak Capacity	400 p/ph				
Service Frequency	On-demand				
Times of Operation	24/7 (365 days per year)				
Configuration	2 double loops				
Operations	On-demand				
Connections	Ride sharing, Multiple Origins to Multiple Destinations				
Type of vehicle	1 <sup>st</sup> generation ParkShuttle				
Number of Vehicles	4				
Passengers seated/standing	8/4				
Drive	Electric				
Supervisory Control System	SuperFROG				
Track Length	2 loops of 1.000 meters				
Number of Stations	7, on-line				
Berths per station	6 single berth stations, 1 station with 3 berths				
Crossings for Traffic/Pedestrians	6 (all at-grade)/ 12 (all at-grade)				

In the Antibes experiment (Alessandrini, et al., 2005) which is a short route of 1 km length, the average speed is fluctuating between 15 and 20 km/h, whereas the average waiting time (depending on the demand and the number of vehicles employed) ranges between 0.5 and 5 minutes. Finally, the minimum headway between vehicles is calculated to be 2 meters.

Another important project, namely the one in Morgantown, is using a guideway of 8.7 miles with five passenger stations along its route. The total fleet size of this system includes 71 rubber-tired electric vehicles, each with a total capacity of 21 passengers, 8 seated and 13 standing. The dwell time used for boarding and alighting is estimated to be 20 seconds. Further technical characteristics regarding the vehicles used in Morgantown are included in Table A-3. Moreover, in a case study in Singapore (Spieser, et al., 2014), the operation of the automated vehicles has been on demand, with estimated route length of minimum 6.47 km and maximum 13.31 km. The area chosen for this case study has allowed a waiting time for the passengers (driving time from booking to pick-up) of 2.3 minutes.

Physical		Performance			
Length	15' 6"	Control	Automatic Remote		
Height	8' 9"	Propulsion	70 HP DC Motor		
Width	6' 8"	Velocity	30 mph / 44 fps max		
Weight	8,750 lbs empty	Suspension	Air Bag Automatic Levelling		
Wheel Base	127"	Steering	Side Sensity (1.2 sec transfer)		
Tread Width	62"	Brakes	Redundant Dual-Piston Calliper		
Capacity	8 seated, 13 standing	Turning Circle	30' radius		

In the research of Young, et al. (2009), the PRT systems serving the Legends at Village West are described. The vehicles are assumed to run with a velocity of 23 mph, as a weighted average between the design speed of 25 mph for the most of the system and 20 mph for some of the sharper curves. Moreover, the boarding time is assumed to be 1 minute, whereas the off-loading time is assumed to be 30 seconds. The average waiting time of the vehicles is less than 3 minutes, in order to attract the public transport movers market. The guideway of the system is estimated to be in total 9.7 miles, with a total number of intermediate stops of 26. Finally, the design velocity of 25 mph has revealed an average travel time of 4 and maximum 6 minutes. Though, a lower speed could preserve a high operational service as well, as long as the speed will be not lower than 20 mph.

Based on the research of McDonald (2003), the general outcome, regarding the operational characteristics of the automated transport system, is that the automated vehicles are more suitable for short distances and dedicated lanes or using elevated structures, in order to prevent the mixture with manually driven vehicles and pedestrians. Moreover, high service frequency or on-demand operation is considered to be important. Short waiting times, distances between stops and careful network design are essential elements for the new modes' success, while the operational speed (for safety reasons) should be lower than 80 km/h.

## **B. APPENDIX** Visualization of potential zones per train station in the province of Utrecht

This Appendix is providing visual identification of the most potential zones for all the 7 train stations examined in the train station identification level in criterion 1.3 (the 8<sup>th</sup> train station resulted in this criterion, namely Hollandsche Rading, had no potential zone around it).





Figure B.1: a) Left: Train station Abcoude with its potential zones b) Right: Train station Bilthoven with its potential zones





Figure B.2: a) Left: Train station Den Dolder with its potential zones b) Right: Train station Maarn with its potential zones





Figure B.3: a) Left: Train station Utrecht Lunetten with its potential zones b) Right: Train station Veenendaal Centrum-Veenendaal West with its potential zones

## C. APPENDIX

# Time-space diagrams for synchronization of trains and automated vehicles

Here, the time-space diagrams of the trains and the automated vehicles for the evening and rest of the day period are presented. The purpose of these diagrams is to define the synchronization of the operation of the automated vehicles (schedule) with the respective operation of Utrecht Centraal-Veenendaal Centrum-Utrecht Centraal train in Veenendaal Centrum, based on the current schedules of the trains and the route travel times of the automated vehicles in each time period per case. Moreover, with these diagrams, the minimum number of automated vehicles per case required is determined, in order to accomplish this synchronization.



Figure C.1: a) Up left: Time-space diagram for the Utr. Centraal-Veenendaal Centrum-Utr. Centraal train in the evening peak b) Down-Left: Time-space diagram for automated vehicles in case 1 in the evening peak c) Down-Right: Time-space diagram for automated vehicles in case 2 in the evening peak



Figure C.2: a) Up left: Time-space diagram for the Utr. Centraal-Veenendaal Centrum-Utr. Centraal train in the rest of the day b) Down-Left: Time-space diagram for automated vehicles in case 1 in the rest of the day c) Down-Right: Time-space diagram for automated vehicles in case 2 in the rest of the day

# D. APPENDIX Evaluation criteria

This Appendix is describing all the evaluation criteria used for the first set of criteria (demand-related criteria and CBA), as well as all the input data that are necessary for the quantification of the evaluation criteria.

#### **D.1 Demand-Related Criteria**

Table D-1 and Table D-2 illustrate the distribution of the AV users (on-board passengers) per AV stop for each direction of the routes that are determined for cases 1 and 2.

#### Table D-1: AV users in case 1

Case 1: Current Bus Line Based Route	AV Trips								
Direction 1: Zone 2298->2307	Morning Peak			Rest of the Day			Evening Peak		
Name of Stop	Boarding Passengers	Alighting Passengers	Total (On- board Passengers)	Boarding Passengers	Alighting Passengers	Total (On- board Passengers)	Boarding Passengers	Alighting Passengers	Total (On- board Passengers)
Veenendaal 2298	28	0	28	37	0	37	25	0	25
Veenendaal 2301C	7	0	35	10	0	48	7	0	32
84302, Veenendaal 't Boveneind	1	0	36	18	0	66	4	0	36
86567	0	0	36	0	0	66	0	0	36
108840, Veenendaal_2301	4	25	15	6	33	38	19	16	40
39128	0	0	15	0	0	38	0	0	40
84304, Veenendaal G.V. Schoonbekestraat	1	0	15	3	0	41	12	6	46
86560	0	0	15	0	0	41	0	0	46
84300, Veenendaal Raadhuisstraat	3	3	15	8	13	36	4	9	42
84301, Veenendaal Raadhuisstraat	0	0	15	0	0	36	0	0	42
39120, Veenendaal, Stationssingel	0	0	15	0	0	36	0	0	42
1216, Veenendaal, Station Centrum Kerkewijk	16	8	23	26	9	54	25	15	52

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84299, Veenendaal, Station Centrum Kerkewijk	0	0	23	0	0	54	0	0	52
Veenendaal Jan vermeerstraat	1	3	21	9	5	58	4	6	50
Veenendaal Rembrandtpark	0	0	21	0	0	58	0	0	50
Veenendaal 2310	2	17	7	9	34	34	7	34	23
Veenendaal 2307	0	7	0	0	34	0	0	23	0
Total	63	63		127	127		108	108	
Direction 2: Zone 2307->2298									
Name of Stop									
Veenendaal 2307	16	0	16	27	0	27	14	0	14
Veenendaal 2310	19	4	32	25	9	42	21	4	30
Veenendaal Rembrandtpark	0	0	32	0	0	42	0	0	30
Veenendaal Jan vermeerstraat	9	1	39	7	3	47	10	2	39
84299, Veenendaal, Station Centrum Kerkewijk	0	0	39	0	0	47	0	0	39
1216, Veenendaal, Station Centrum Kerkewijk	3	11	31	10	7	50	31	6	64
39120, Veenendaal, Stationssingel	0	0	31	0	0	50	0	0	64
84301, Veenendaal Raadhuisstraat	0	0	31	0	0	50	0	0	64
84300, Veenendaal Raadhuisstraat	4	4	32	13	6	57	4	6	62
86560	0	0	32	0	0	57	0	0	62
84304, Veenendaal G.V. Schoonbekestraat	3	1	35	10	1	66	7	33	37
39128	0	0	35	0	0	66	0	0	37
108840, Veenendaal 2301	8	27	16	13	43	36	24	18	43
86567	0	0	16	0	0	36	0	0	43
84302, Veenendaal 't Boveneind	1	0	17	28	0	63	6	0	48
Veenendaal 2301C	0	0	17	0	0	63	0	0	48
Veenendaal 2298	0	17	0	0	63	0	0	48	0
Total	65	65		131	131		117	117	

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#### Table D-2: AV users of case 2

Case 2: Shortest Path Based Route					AV Trips				
Direction 1: Zone 2298->2307		Morning Peak			Rest of the Day			<b>Evening Peak</b>	
Name of Stop	Boarding Passengers	Alighting Passengers	Total (On- board Passengers)	Boarding Passengers	Alighting Passengers	Total (On- board Passengers)	Boarding Passengers	Alighting Passengers	Total (On- board Passengers)
Veenendaal 2298	25	0	25	35	0	35	21	0	21
Veenendaal 2301	4	17	12	30	25	40	25	13	33
Veenendaal 2301B	8	2	17	14	10	43	9	8	34
84301, Veenendaal Raadhuisstraat	8	8	17	10	11	41	11	10	35
39120, Veenendaal, Stationssingel	0	0	17	0	0	41	0	0	35
1216, Veenendaal, Station Centrum Kerkewijk	1	5	13	9	3	47	5	3	38
84299, Veenendaal, Station Centrum Kerkewijk	0	0	13	0	0	47	0	0	38
Veenendaal 2310	2	10	5	11	27	32	9	23	23
Rhenen, Rhenendael	0	0	5	0	0	32	0	0	23
Veenendaal 2307B	0	5	0	0	32	0	0	23	0
Total	48	48		108	108		80	80	
Direction 2: Zone 2307->2298									
Name of Stop									
Veenendaal 2307B	20	0	20	31	0	31	16	0	16
Rhenen, Rhenendael	0	0	20	0	0	31	0	0	16
Veenendaal 2310	20	5	35	21	11	41	32	7	41
84299, Veenendaal, Station Centrum Kerkewijk	0	0	34,96	0	0	40,72	0	0	41
1216, Veenendaal, Station Centrum Kerkewijk	4	7	32	13	5	48	9	3	47

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39120, Veenendaal, Stationssingel	0	0	32	0	0	48	0	0	47
84301, Veenendaal Raadhuisstraat	4	12	24	6	11	43	8	26	30
Veenendaal 2301B	2	9	17	6	21	28	2	17	14
Veenendaal 2301	4	16	6	27	24	31	25	12	27
Veenendaal 2298	0	6	0	0	31	0	0	27	0
Total	55	55		103	103		92	92	

#### D.2 **CBA** Criteria

This part involves the detailed determination of the input data per CBA criterion and the respective calculation of the  $\Delta$  and PV.

#### Passenger (fare) effects of former BTM users switched to automated vehicles

For the determination of this criterion, the input data used are three main sets. The first set of data is the BTM demand changes between the two cases and the current situation in passengers for all consecutive BTM stops (on-board passengers per day for each bus stop). The reference lines are the ones connecting the train station of Veenendaal Centrum with the selected zones (2298, 2301, 2307 and 2310), while the bus stops used are only the bus stops around these zones (same or close to the chosen AV stops per case). The second set of data is the respective distances of consecutive stops. The final set is the fare difference between the current BTM system and the AV fare system that the former BTM users are saving from their switch to the automated vehicles. It is assumed here that only lines 80, 81 and 83 are affected by the introduction of the automated vehicles into the transport system of Veenendaal and no other BTM lines. The fare system of the BTM lines is the same as the one used from the OmniTRANS model. The determination of the BTM demand difference in passenger-km ( $\Delta$ ) and the respective Present Value of it (in  $\in$ ) are calculated based on the following equations:

$$\Delta_{1} = \sum_{\substack{All \ bus \ lines \\ investigated \\ investigated \\ \times 52 \ Weeks \times 30 \ Years}} \sum_{\substack{BTM \ Onboard \ Passengers_{Current \ Situation-Case \\ \times \ Consecutive \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ bus \ stops \\ \times \ State \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ bus \ stops \\ \times \ State \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ bus \ stops \\ \times \ State \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ bus \ stops \\ \times \ State \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ bus \ stops \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ bus \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ bus \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ bus \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ bus \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ bus \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ bus \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ bus \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ bus \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ bus \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ Bl \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ Bl \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ Bl \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ Bl \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ Bl \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ Bl \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ Bl \ Stops \ Distance \\ > 0 \ Years}} \sum_{\substack{All \ Bl \ Stops \ Distance \ Dista$$

$$PV_1 = \Delta_1 \times (Fare_{BTM} - Fare_{AV})$$

All input data are presented in Table D-3, in which all three bus lines are included (80, 81 and 83) and the investigated BTM stops, as defined previously. The Present Value here is calculated without the interest rate of 5,5%, which is applied, though, in Table 4-3 of the CBA. The BTM fare starts from 0,80 €/km, while the starting fare for the automated vehicles is 0,45 €/km. Finally, the negative values in the first two columns represent the decrease of BTM user-km in both cases, compared to the current situation, while the positive values in the last two columns represent the fare benefits that former BTM users gain by the switch to the new (lower cost) mode.

Table D-3: Passenger (fare) effects for former BTM users switched to AVs in cases 1 and 2

	BTM Demand Effects Per Day For All BTM Lines (Passengers Difference*km)	BTM Demand Effects For 30 Years For All BTM Lines ( $\Delta_1$ ) (Passengers Difference*km)	Total Monetary Fare Effects Per Day For All BTM Lines (From Passenger Perspective)	Total Monetary Fare Effects For 30 Years For All BTM Lines (PV <sub>1</sub> ) (From Passenger Perspective)
Case 1: Current Bus Line Based Route	-479	-4482091	+168	+1568732
Case 2: Shortest Path Based Route	-837	-7835755	+293	+2742514

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#### Passenger (fare) effects of former car users switched to automated vehicles

The input data required for this criterion are again three main data sets. The first is the total car volume-km differences between the reference case and each of the two cases. The second is the fuel consumption (I/km), while the final set is the difference between the fuel price per litre/km and the respective AV fare per km, in order to determine the fare effects (benefits) of the former car users that switched to the new mode. Regarding the fuel consumption of each vehicle, it is assumed that all cars are conventional gasoline vehicles, each of which is consuming approximately 9,5 l per 100 km (or 0,095 l/km), according to Granovskii, et al. (2006). Finally, the fuel price per litre is based on the fuel price in the Netherlands in July 2015 (http://www.globalpetrolprices.com/) and is equal to 1,78  $\in$ /l. All the above and the respective operational car cost changes per day and finally for 30 years (time horizon of CBA) are calculated based on the following equations:

 $\Delta_2 = \# Cars - km_{Current\ Situation-Case} \times Fuel\ Consumption \times 6\ Days \times 52\ Weeks \times 30\ Years$ 

$$PV_2 = \Delta_2 \times (Fuel Price_{Car} - Fare_{AV})$$

The application of both equations, for the determination of the  $\Delta$  and the present value for each case, is depicted in Table D-4.

	Fuel Price (€/l/km)	Fuel Consumption (I/km)	Passenger Effects For Former Car Users Per Day (Car-km Difference*Fuel Consumption)	Passenger Effects For Former Car Users For 30 Years ( $\Delta_2$ )	Monetary Passenger Effects For Former Car Users Per Day (€)	Monetary Passenger Effects For Former Car Users For 30 Years (€) (PV <sub>2</sub> )
Case 1: Current Bus Line Based Route	1,78	0,095	-132	-1239041	+236	+2205492
Case 2: Shortest Path Based Route	1,78	0,095	-187	-1748538	+333	+3112398

Table D-4: Passenger (fare) effects of former car users that switched to AVs for cases 1 and 2

The negative values represent the decrease of the car-km in both cases, compared to the current situation, whereas the positive values represent the fare benefits of former car users from switching to AVs that are having lower fare price/km than the car. Finally, the Present Values calculated per case are without the incorporation of the interest rate, which is applied, though, in the CBA (Table 4-3).

## Passenger (fare) effects of other mode users switched to automated vehicles

For the determination of this criterion, two separate actions need to be realised. The first action is the determination of the total daily demand in passenger-km for automated vehicles (all users included), and the respective Present Value for 2040. The second is the subtraction of the BTM and car Present Values ( $PV_1$ ,  $PV_2$ ) of users that switched to the automated vehicles (defined from the previous two criteria) from the total AV Present Value for each case. The total daily demand (on-board passengers/travelled distance) of the automated vehicles is calculated for each pair of consecutive AV stops of both cases. The

daily monetary fare effects for all AV users is based on the AV fare system per km (chapter 3.5.6) and projected to 2040. The final step is the subtraction of the BTM and car Present Values from the Present Value of the total AV users, so that the final Present Value for the rest of the AV users is defined ( $PV_3$ ). The Present Value of the rest of the AV users (excluding the BTM and car users that switched to AVs) is calculated according to the following equation (the interest rate of 5,5% is not included, but is incorporated into the CBA (Table 4-3)):

$$PV_{3} = \left(\sum_{\substack{All \ bus \ stops \\ investigated}} \left( \begin{array}{c} Total \ AV \ Onboard \ Passengers_{Case} \\ \times \ Consecutive \ Stops \ Distance \end{array} \right) \times 6 \ Days \times 52 \ Weeks \times 30 \ Years \right)$$

As mentioned in chapter 4.3.4, this criterion is identifying the rest of the users, in which also new AV users are included that did not switch from other modes (pedestrians, cyclists etc.). To capture this new demand, the rule of half would be the correct estimation of the fare effects for this new demand. Though, in this study the new AV users are not easily identified, so the application of the rule of half would underestimate the total fare effects, since it would be applied to all these switched users and not only to the new AV users. So, the Present Value of the rest of the AV users is determined without the rule of half, an action that overestimates slightly the final fare effects.

The Present Value for the total AV demand in 2040 is calculated per case in Table D-5 and Table D-6, while the final Present Value per case ( $PV_3$ ), after the subtraction process, is presented in Table D-7. The negative values in Table D-7 refer to the costs that the rest of the AV users are facing for switching from their previous mode choices (pedestrians, cyclists, new AV users and BTM users that switched to the automated vehicles and travel along longer routes than they used to).

#### Table D-5: Passenger (fare) effects for all AV users in case 1

	Case 1: Current Bus Line Based Route											
Direction 1: Zone 2298- >2307	Fare	Consecutive Stop Distance	Morning Peak	Rest of the Day	Evening Peak	Monetary Fare Effects (Per	Total Monetary Fare Effects For 30					
Name of Stop	(€)	(km)	Total (On-board Passengers)	Total (On-board Passengers)	Total (On-board Passengers)	(€*km*#of Passengers)	Passengers)					
Veenendaal 2298	-	-	27,81	37,15	25,07	-						
Veenendaal 2301C	0,45	0,35	34,87	47,55	31,82	14,18						
84302, Veenendaal 't Boveneind	0,45	0,7	35,73	65,66	36,15	35,99						
86567	-	-	35,73	65,66	36,15	-						
108840_Veenendaal_2301	0,45	0,3	14,68	38,21	40,04	18,57						
39128	-	-	14,68	38,21	40,04	-						
84304, Veenendaal G.V. Schoonbekestraat	0,45	0,42	15,32	40,84	46,31	17,56						
86560	-	-	15,32	40,84	46,31	-						
84300, Veenendaal Raadhuisstraat	0,45	0,81	14,67	36,44	41,93	37,35						
84301, Veenendaal Raadhuisstraat	-	-	14,67	36,44	41,93	-						
39120, Veenendaal, Stationssingel	-	-	14,67	36,44	41,93	-						
1216, Veenendaal, Station Centrum Kerkewijk	0,45	0,72	22,56	54,15	51,83	30,14						
84299, Veenendaal, Station Centrum Kerkewijk	-	-	22,56	54,15	51,83	-						
Veenendaal Jan vermeerstraat	0,45	0,44	21,07	58,31	49,73	25,45						
Veenendaal Rembrandtpark	-	-	21,07	58,31	49,73	-						
Veenendaal 2310	0,45	0,6	6,66	34,08	22,75	34,86						
Veenendaal 2307	0,55	2,55	0	0	0	89,04						
Total						303	2837462					
Direction 2: Zone 2307- >2298												
Number of Stop												
Veenendaal 2307			16,34	26,55	13,71							
Veenendaal 2310	0,55	2,55	31,77	42,33	30,21	79,38						

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Veenendaal Rembrandtpark	0,45	0,6	31,77	42,33	30,21	28,16	
Veenendaal Jan	-	-	39,3	46,59	38,68	-	
vermeerstraat			,-	-,	/		
84299, Veenendaal, Station	0.45	0.44	39.3	46.59	38.68	24.66	
Centrum Kerkewijk	-, -	-,	,-	-,	,	,	
1216, Veenendaal, Station	-	-	31.14	49.75	63.56	-	
Centrum Kerkewijk			01)11		00,00		
39120, Veenendaal,	0.45	0.72	31 14	49 75	63 56	46.80	
Stationssingel	0,43	0,72	51,14	+5,75	03,30	40,00	
84301, Veenendaal			21.14	40 7E	62 E6		
Raadhuisstraat	-	-	51,14	49,75	05,50	-	
84300, Veenendaal			21.02	EC E2	62.27		
Raadhuisstraat	-	-	51,92	50,55	02,57	-	
86560	0,45	0,81	31,92	56,53	62,37	54,97	
84304, Veenendaal G.V.			24.70	CE 54	20.05		
Schoonbekestraat	-	-	34,76	65,51	36,65	-	
39128	0,45	0,42	34,76	65,51	36,65	25,88	
108840_Veenendaal_2301	-	-	15,71	35,5	42,79	-	
86567	0,45	0,3	15,71	35,5	42,79	12,69	
84302, Veenendaal 't			10.05	69.45	40.00		
Boveneind	-	-	16,95	63,15	48,33	-	
Veenendaal 2301C	0,45	0,7	17,19	63,31	48,45	40,46	
Veenendaal 2298	0,45	0,35	0	0	0	20,31	
Total						333	3119863

#### Table D-6: Passenger (fare) effects for all AV users in case 2

	Case 2: Shortest Path Based Route											
Direction 1: Zone 2298- >2307	Fare	Consecutive	Morning Peak	Rest of the Day	Evening Peak	Monetary Fare Effects (Per	Total Monetary Fare Effects For 30 Years of Operation (€*km*#of Passengers)					
Name of Stop	(€)	(km)	Total (On-board Passengers)	Total (On-board Passengers)	Total (On-board Passengers)	(€*km*#of Passengers)						
Veenendaal 2298	-	-	24,53	34,57	21,21	-						
Veenendaal 2301	0,45	1,05	11,64	39,87	32,93	37,95						
Veenendaal 2301B	0,45	0,61	17,07	43,35	33,98	23,18						
84301, Veenendaal Raadhuisstraat	0,45	0,77	16,89	41,46	35,37	32,71						
39120, Veenendaal,	-	-	16,89	41,46	35,37	-						

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Stationssingel							
1216, Veenendaal, Station Centrum Kerkewijk	0,45	0,53	13,33	47,39	37,73	22,35	
84299, Veenendaal, Station Centrum Kerkewijk	-	-	13,33	47,39	37,73	-	
Veenendaal 2310	0,45	0,85	5,23	31,68	23,17	37,66	
Rhenen, Rhenendael	-	-	5,23	31,68	23,17	-	
Veenendaal 2307B	0,55	2,95	0	0	0	97,48	
Total						251	2352393
Direction 2: Zone 2307- >2298							
Number of Stop							
Veenendaal 2307B			20,09	30,81	15,61		
Rhenen, Rhenendael	0,55	2,95	20,09	30,81	15,61	107,91	
Veenendaal 2310	-	-	34,96	40,72	40,74	-	
84299, Veenendaal, Station Centrum Kerkewijk	0,45	0,85	34,96	40,72	40,74	44,53	
1216, Veenendaal, Station Centrum Kerkewijk	-	-	32,42	48,04	47,2	-	
39120, Veenendaal, Stationssingel	0,45	0,53	32,42	48,04	47,2	30,45	
84301, Veenendaal Raadhuisstraat	-	-	24,31	43,39	29,68	-	
Veenendaal 2301B	0,45	0,77	17,06	28,18	14,15	33,74	
Veenendaal 2301	0,45	0,61	5,5	30,5	27,48	16,30	
Veenendaal 2298	0,45	1,05	0	0	0	29,99	
Total						263	2461016

Table D-7: Present values for rest of AV users (excluding former BTM and car users)

	Monetary Passenger Effects For All AV Users For 30 Years (€)	Monetary Passenger Effects For Rest of AV Users Excluding Former BTM and Car Users For 30 Years (€) (PV <sub>3</sub> )	
Case 1: Current Bus Line Based Route	-5957325	-3382815	
Case 2: Shortest Path Based Route	-4813409	-500477	

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# AV operator (fare) effects from all AV users

This criterion determines the fare effects from all AV users for the AV operator. The Present Value ( $PV_4$ ) for this criterion per case is the monetary passenger effects for all AV users for 30 years, as presented in Table D-7 in the first column. The only difference is that for the AV operator, these effects are positive, since they are translated into revenues for the operator, instead of costs as it is valued in the previous criterion.

# BTM (fare) effects for operator

The BTM fare effects from the operator's point of view are determined as the number of BTM users, in passenger-km, that switched to automated vehicles until 2040 ( $\Delta_5$ ) and the respective monetary effects of this change ( $PV_5$ ). This process is the same as in criterion "Passenger (fare) effects of former BTM users switched to automated vehicles", with the only difference that instead of applying in the Present Value the fare difference between the BTM and the AV system, for the operator the Present Value is calculated based on the fare of the BTM only. This choice is justified by the assumption that the AV and BTM operator is different, so the loss of the BTM operator is in relation to the total fare of the BTM system. The respective equations that calculate the  $\Delta$  and PV for the BTM operator are presented below (the interest rate is not included here, but is incorporated in the CBA (Table 4-3)):

$$\Delta_{5} = \sum_{\substack{All \ bus \ lines \\ investigated \\ investigated \\ \times 52 \ Weeks \times 30 \ Years}} \sum_{\substack{BTM \ Onboard \ Passengers_{Current \ Situation-Case \\ \times \ Consecutive \ Stops \ Distance \\ \times \ 52 \ Weeks \times 30 \ Years}} \left( \sum_{\substack{BTM \ Onboard \ Passengers_{Current \ Situation-Case \\ \times \ Stops \ Distance \ D$$

$$PV_5 = \Delta_5 \times Fare_{BTM}$$

The outcomes from the application of the previous equations are presented in Table D-8.

	BTM Demand Effects Per Day For All BTM Lines (Passengers Difference*km)	BTM Demand Effects For 30 Years For All BTM Lines (Δ <sub>5</sub> ) (Passengers Difference*km)	Total Monetary Fare Effects Per Day For All BTM Lines (From Passenger Perspective)	Total Monetary Fare Effects For 30 Years For All BTM Lines (PV <sub>5</sub> ) (From Passenger Perspective)
Case 1: Current Bus Line Based Route	-479	-4482091	-492	-4610151
Case 2: Shortest Path Based Route	-837	-7835755	-861	-8059634

Table D-8: BTM fare effects from BTM operator's perspective

The negative values refer to the decrease of BTM users and the respective loss of revenues for the BTM operator.

## BTM in-vehicle time effects- BTM waiting time effects

The total in vehicle and total waiting travel time effects for BTM users that remained to the BTM system are defined as the difference of travel time between the reference case (without automated vehicles) and each of the two route cases (after the introduction of the automated vehicles). These values refer to the total network for the entire day and for all access/egress mode combinations. Furthermore, these data are transformed into annual data and projected for the year 2040, so 30 years of operational timeline. Finally, the VoT for the BTM mode is used in order to translate the time data into monetary values. The respective  $\Delta$  and PV values are calculated based on the following equations (the interest rate is not included here, but is incorporated in the CBA (Table 4-3)):

 $\Delta_6 = (BTM In - Vehicle Time_{Current Situation-Case}/60 Minutes) \times 6 Days \times 52 Weeks \\ \times 30 Years$ 

 $\Delta_7 = (BTM Waiting Time_{Current Situation-Case}/60 Minutes) \times 6 Days \times 52 Weeks \times 30 Years$ 

$$PV_6 = \Delta_6 \times VoT_{BTM}$$
$$PV_7 = \Delta_7 \times VoT_{BTM}$$

The changes for the in-vehicle and waiting travel times ( $\Delta_6$ ,  $\Delta_7$ ) of the BTM users, as well as the respective Present Values (PV<sub>6</sub>, PV<sub>7</sub>), are illustrated in Table D-9.

	In Vehicle Time Effects Per Day (min.)	Waiting Time Effects Per Day (min.)	In Vehicle Time Effects For 30 Years (h) ( $\Delta_6$ )	Waiting Time Effects For 30 Years (h) ( $\Delta_7$ )	BTM VoT (€/h)	Monetary In Vehicle Time Effects For 30 Years (€) (PV <sub>6</sub> )	Monetary Waiting Time Effects For 30 Years (€) (PV <sub>7</sub> )
Case 1: Current Bus Line Based Route	+46218	-52669	+7209993	-8216416	4,92	+35473167	-40424768
Case 2: Shortest Path Based Route	+37939	+130155	+13128525	+20304112	4,92	+64592345	+99896229

Table D-9: Travel time effects of BTM network per case

The positive values are representing the travel time benefits for the BTM users after the implementation of the automated vehicles, compared to the current situation. On the other hand, the negative values depict the costs for the BTM users, after the introduction of the automated vehicles, in contrast to the reference case.

## Car in-vehicle time effects

According to the outcomes of the run of the OmniTRANS model for Utrecht, the introduction of the automated vehicles into the existing network has not affected the in-vehicle travel time of the car transport network. So, the respective values  $\Delta_8$  and  $PV_8$  for this criterion are 0 in this case study.

## Construction costs of new AV stops

For the construction costs per AV stop, the reference cost of 500.000 €/stop is used, based on the survey of Kerr, et al. (2005). This value is checked by comparing it with the respective construction cost of new regular bus stops. This cost appeared to be 450.000 €/stop for a

high tech bus stop, justifying the choice of the AV stop construction cost. Moreover, the total construction costs of the AV stops are dependent on the number of stops built, which differs between the two cases (for the first case, 3 new AV stops are built, whereas for the second case 5). The respective equation to calculate the AV stop construction cost per case ( $PV_9$ ) is determined as (the interest rate is not included here, but is incorporated in the CBA (Table 4-3)):

#### *PV*<sub>9</sub> = #*AV Stops* × *AV Stop Construction Cost*

The outcomes of the application of the above equation are in detail presented in Table D-10.

Table D-10: Construction costs of AV stops

	Case 1: Current Bus Line Based Route	Case 2: Shortest Path Based Route
Number of New AV Stops	3	5
Construction Costs Per Stop (€)	500.000	500.000
Total Stop Costs (PV <sub>9</sub> )	1500000	2500000

From the equation it is already implied that the construction costs are assumed to be spent during the first year of implementing the automated vehicles to the system, namely the year 2010 (which is the reference year of the CBA). This means that these expenses are considered as investment costs of the first year and are not projected to the year of 2040.

#### Purchase of the automated vehicles

Following exactly the same logic as in the previous criterion, the purchase cost per vehicle is assumed to be 100.000  $\in$  (CityMobil2, 2015). Each case (according to chapter 3.5.7) is requested to be equipped with 4 automated vehicles. The equation for calculating the purchase cost per case (PV<sub>10</sub>) is illustrated below (the interest rate is not included here, but is incorporated in the CBA (Table 4-3)):

#### $PV_{10} = #AV Vehicles \times AV Purchase Cost$

The total costs per case are presented below (Table D-11). Again, these costs are considered as investment costs covered during the first year of implementation of the project, the same as for the AV stop investment costs.

#### Table D-11: Purchase costs of automated vehicles

	Case 1: Current Bus Line Based Route	Case 2: Shortest Path Based Route	
Number of Automated Vehicles	4	4	
Purchase Costs Per Vehicle (€)	100.000	100.000	
Total Purchase Costs (PV <sub>10</sub> )	400000	400000	

## Operational and maintenance costs of automated vehicles

According to Tegner (2003), the annual operational and maintenance costs are determined per track-km and are considered as 140.000 €/km. It is important to mention two points here:

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- In the operational and maintenance costs for automated vehicles, researchers include also electricity (power) expenses (Kerr, et al., 2005). So, it is assumed that the above O&M annual cost takes into consideration also the electricity costs required for the operation of the automated vehicles.
- Based on the survey of Tegner (2003), these annual costs per track-km refer to the entire system, so for all the vehicles operating the route. So, it is assumed that this amount corresponds to the total operational and maintenance costs per km, so these costs are only dependent on the total route km.

The equation that defines the operational and maintenance costs ( $PV_{11}$ ) until 2040 for each case is presented below (the interest rate is not included here, but is incorporated in the CBA (Table 4-3)):

$$PV_{11} = Route \ Length \times 0\&M \ AV \ Costs \times 30 \ Years$$

So, based on the above, the total costs per year for each case (with the respective route length), are presented in Table D-12.

#### Table D-12: O&M costs of automated vehicles

	Case 1: Current Bus Line Based Route	Case 2: Shortest Path Based Route
Route Length (km)	13,78	13,54
Operational and Maintenance Costs/Year (€)	140000	140000
Total O&M Costs (For 30 Years) (€) (PV <sub>11</sub> )	57876000	56868000

## AV externality effects

Taking into account that the automated vehicles are operating as electric vehicles, the externalities are captured in respect to electric vehicles. Based on Greenstone & Looney (2012), the annual externality costs per electric vehicle are calculated to reach the amount of  $355 \in$ . The equation that determines the total externality costs for the AVs until 2040 (PV<sub>12</sub>) is depicted below (the interest rate is not included here, but is incorporated in the CBA (Table 4-3)):

$$PV_{12} = #AV Vehicles \times AV Externality Costs \times 30 Years$$

Each case has in total 4 vehicles operating for the given routes, so the total annual and 30-year externality costs for each case are presented in Table D-13 below.

#### Table D-13: AV externality costs

	Case 1: Current Bus Line Based Route	Case 2: Shortest Path Based Route
Number of Automated Vehicles	4	4
External Costs/Vehicle/Year (€)	355	355
Total Externality Costs For 30 Years ( $\in$ ) (PV <sub>12</sub> )	42600	42600

# Car externality effects

Based on the car volume-km changes between the reference case and the two route cases with the automated vehicles (determined in criterion "Passenger (fare) effects of former car users switched to automated vehicles"), the respective externality cost changes are defined. So, according to Bakker & Zwaneveld (2009), the externality costs for a gasoline vehicle within an urban area (as the case of Veenendaal) in the Netherlands are 7,16 €/vehicle-km. The total externality effects of the car users' switch to the automated vehicles for the society  $(\Delta_{13})$  and the respective monetary externality effects (PV<sub>13</sub>) per case, are determined according to the following equation (the interest rate is not included here, but is incorporated in the CBA (Table 4-3)):

$$\Delta_{13} = \#Cars - km_{Current Situation-Case} \times 6 Days \times 52 Weeks \times 30 Years$$

 $PV_{13} = \Delta_{13} \times Car Externality Costs$ 

The total externality costs per case for an annual and 30-year operational time frame are depicted in Table D-14.

Table D-14: Car externality costs

	Car Volumes-Km Effects Per Day (Compared to Current Situation)	Car Volumes-Km Effects For 30 Years (Compared to Current Situation) ( $\Delta_{13}$ )	Externality Costs (€/vehicle- km)	Total Externality Cost Effects Per Day (€)	Total Externality Costs Effects For 30 Years (€) (PV <sub>13</sub> )
Case 1: Current Bus Line Based Route	-1393	-13042533	7,16	+9977	+93384535
Case 2: Shortest Path Based Route	-1966	-18405663	7,16	+14080	+131784548

The negative values reflect the decrease of car-km after the implementation of the automated vehicles, compared to the current situation, while the positive values refer to the benefits the society is gaining from the decrease of car-km in terms of externality costs.

# Levy effects

The direct impact of the car-km changes in the network after the implementation of the automated vehicles is on the fuel taxes gained from the government by the car users. The tax percentage derived from each fuel litre is 70%. Based on this percentage, and according to the outcomes of Table D-4, the final levy effect is calculated for the government. The equation that determines the value of car-km changes ( $\Delta_{14}$ ) and the respective levy effects for the government in monetary values  $(PV_{14})$  is presented below (the interest rate is not included here, but it is incorporated in the CBA (Table 4-3)):

 $\Delta_{14} = Percentage \ of \ Levy \times \#Cars - km_{Current \ Situation-Case} \times Fuel \ Consumption \times 6 \ Days$  $\times$  52 Weeks  $\times$  30 Years

$$PV_{14} = \Delta_{14} \times Fuel Price_{Car}$$

The levy loss outcomes for each route case, in comparison to the reference case, are summarised in Table D-15 below.

#### Table D-15: Levy effects

	Levy Over Operational Car Costs (%)	Monetary Car Switch Effects For Car Users For 30 Years (€)	Monetary Levy Effects For 30 Years (€) (PV <sub>14</sub> )
Case 1: Current Bus Line Based Route	70	-2205492	-1543845
Case 2: Shortest Path Based Route	70	-3112398	-2178678

The negative values are representing the decrease of car-km after the implementation of the automated vehicles, compared to the reference case, as well as the levy loss of the government of this car-km decrease.

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