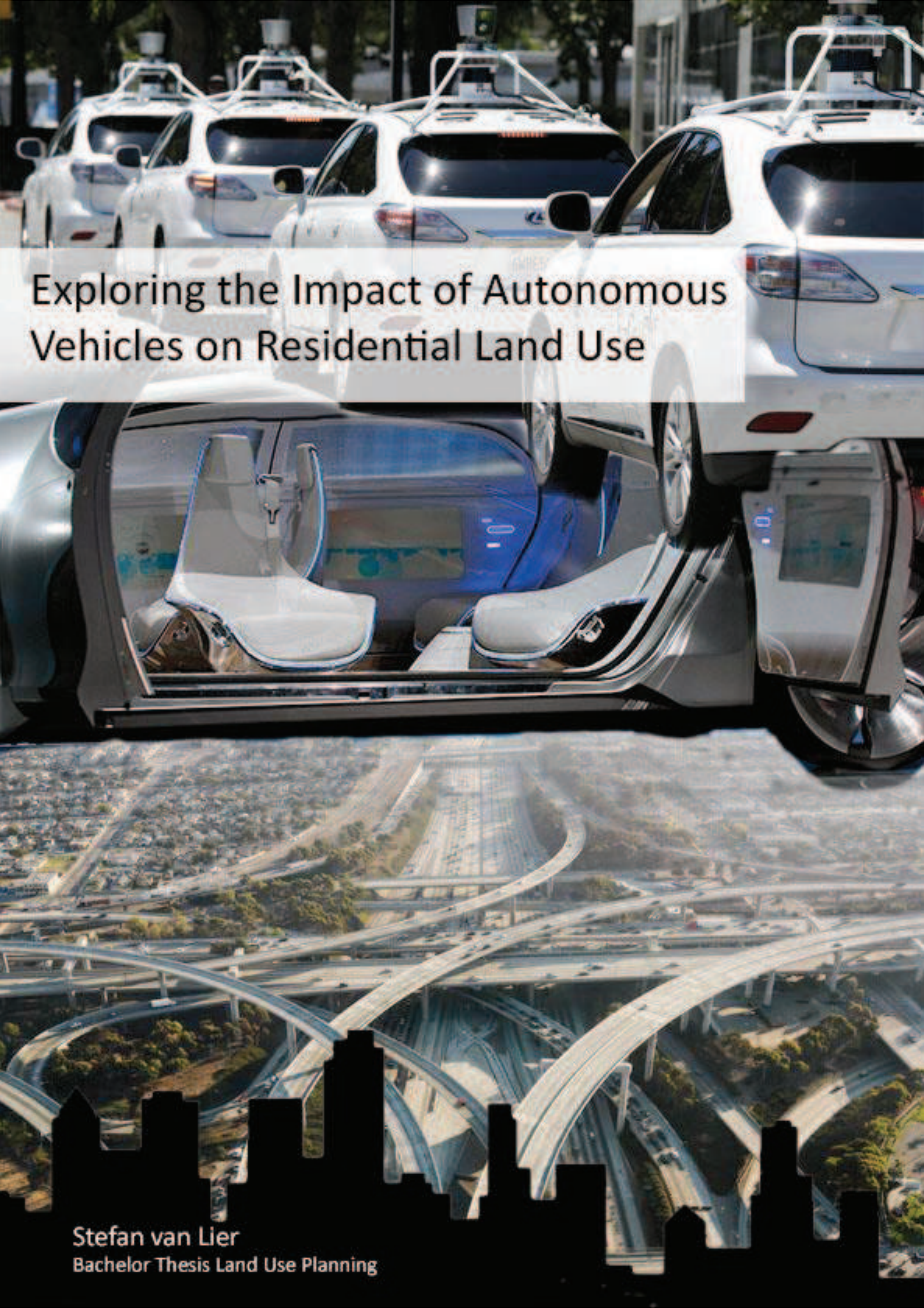
Exploring the Impact of Autonomous Vehicles on Residential Land Use



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ABSTRACT

This study focuses on the relatively unexamined implications of Autonomous passenger vehicles for residential land use. More specifically, the different impacts Privately-owned Autonomous Vehicles (PAV's) and Shared Autonomous Vehicles (SAV's) have on the energy-intensity of residential land use will be explored. The reason for this is that the vehicle ownership structure of AV's was found to be the most uncertain driving force with at the same time, the highest impact on residential land use. The intuitive logics scenario method will be used in combination with the system dynamics approach to conduct the future exploration. Residential suburbanization in the scenarios is explained by the bundled concept of transport resistance. The plotted scenarios and corresponding causal loop diagrams reveal that the widespread usage of PAV's leads to a higher residential suburbanization tendency than the widespread usage of SAV's. Additionally, the SAV-scenario anticipates a higher housing density and more multimodal transport which results into a more polycentric city structure. The higher residential density of the SAV-scenario is less energy-intensive in terms of both housing and transport. The reasons for the differences between the scenarios are mainly economical. SAV trips are marginally priced and on top of that, SAV's can be more efficiently used and parked which is beneficial in terms of total energy consumption. Besides, the SAV-trip price is directly related to the balance in the supply and demand of trips, the trip price decreases with residential density. PAV's on the other hand, incentivize more and longer trips by conventional pricing where fixed costs are paid in advance and consequently regarded as sunk costs. The residential suburbanization enabled by PAV's is mainly the result of the insufficient counteracting of baseline driving forces of AV's. In other words, the improved comfort and safety, increased speed, and economic benefits AV's offer are not expected to be sufficiently neutralized by price-mechanisms and feedback loops in the PAV-scenario.

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LIST OF ABBREVIATIONS

ACC	Adaptive Cruise Control
AV	Autonomous Vehicle
CACC	Cooperative Adaptive Cruise Control
CBD	Central Business District
CLD	Causal Loop Diagram
PAV	Privately-owned Autonomous Vehicle
SAV	Shared Autonomous Vehicle
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
VKT	Vehicle Kilometres Travelled
VOT	Value of Time
GTC	Generalized Transport Costs

1 INTRODUCTION

Autonomous vehicles (AV's) or self-driving cars have been a hot research topic in the last decade. This is not strange since AV's can potentially reshape the whole mobility system. Partially automated vehicles are already starting to enter the consumer market and are expected to become fully automated in just twenty years (Milakis et al. 2017; Wadud et al. 2016). This would not just have a huge impact on the mobility system but also on the socioeconomic and physical environment. Research on autonomous vehicles however is mainly focused on technical issues regarding safety, capacity, guidance and control (Milakis et al. 2015). These studies usually describe potential benefits of AV's in terms of energy usage, time-saving, safety and efficiency. The Dutch Government has adopted the results of these studies and mentions the benefits of AV's on her website (Rijksoverheid n.d.). Unfortunately, the technology-focused studies often neglect to look at the system-level impacts of AV's. The government website's claim that 'the use of AV's will result in less fuel usage and traffic jams' cannot be made while ignoring the travel demand and land use change effects of AV's. To overcome these shortcomings, this study will explicitly focus on the impact AV's have on land use and travel demand.

2 THEORETICAL FRAMEWORK

As a reaction to the limited view on AV's, several authors have emphasized the need for a more integral look at AV's at the system level (Lauwers 2015; Papa & Lauwers 2015; Wadud et al. 2016). The ripple model developed by van Arem et al. 2014 models the sequential system-wide effects of automated driving and distinguishes short-, medium-, and long-term effects of AV's (see Figure 1). The inner circle (ripple) around 'automated driving' represents short-term effects while the outer circle represents long-term effects. Land use change and location choice implications are part of the second ripple. This ripple contains medium-term effects of automated driving. In order to draw conclusions about third ripple or long-term effects, research about second ripple effects is necessary. After all, the amount of energy consumption and congestion and consequently the degree of sustainability, depends on the spatial configuration of land use functions. Earlier research on the relation between residential density and energy usage has revealed that lower densities lead to a higher transport energy usage per person (Brownstone & Golob 2009; Norman et al. 2006). This implies that in order to say something about the energy footprint of AV's, its spatial impact has to be taken into account. Therefore, to fill the gap between first and third ripple effects, this study will focus on residential location choice implications of automated driving (marked in Figure 1). Besides residential land use implications, the ripple model also anticipates changes in employment and recreational locations. There is even less literature about the effect of AV's on these land use functions (Milakis et al. 2015). On top of that, employment locations are also affected by (autonomous) freight transport which is another topic of study. Therefore, to sufficiently limit the research scope, this study will only focus on residential land use effects of (passenger transport) AV's.

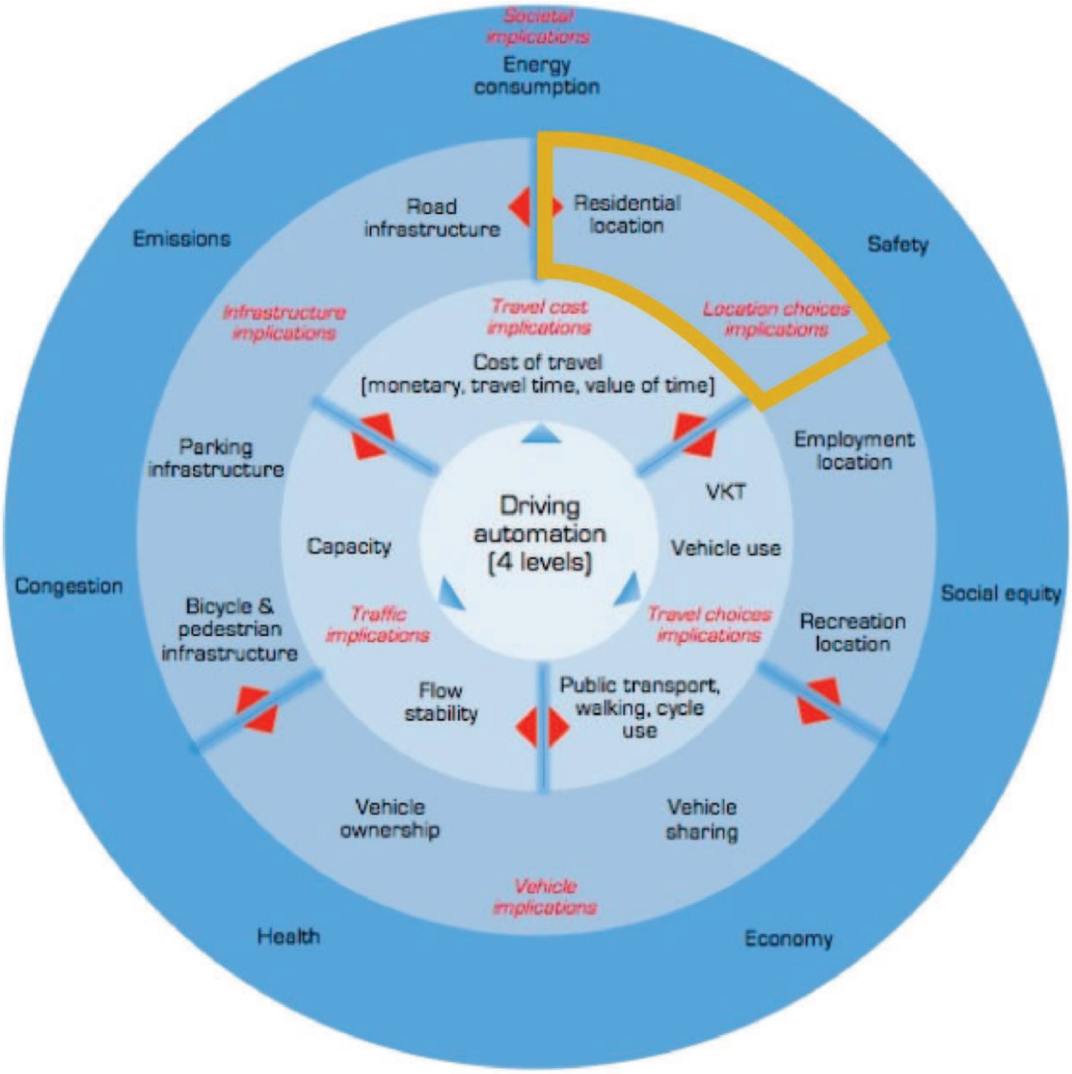

Figure 1: The Ripple Model of automated driving (van Arem et al. 2014).

Only a few recent studies have explored some effects of AV's on general land use under which Gruel & Stanford 2016, Heinrichs & Cyganski 2015, Heinrichs 2015 and Alessandrini et al. 2015. Very recently, the impact of AV's on accessibilities in Switzerland was modelled according to different assumptions by Meyer et al. 2017. To the best of my knowledge, not a single study has been conducted that focuses specifically on residential land use effects of AV's. Because of the great amount of uncertainty that is involved in the development of an autonomous automobility system, almost all land use studies have been explorative. This study will be explorative and scenario-based as well. However, it will use system dynamics to systematically link cause and effect relations of AV-related and land use-related driving forces.

The variables of the earlier described ripple model all interact with each other. Yet, some variables involve a higher degree of uncertainty than others. For example, many scenario studies agree on the assertion that the usage of AV's will result in a decrease of Generalized Transport Costs (GTC) (Smith 2012; Meyer et al. 2017). The reason for this is that the value of time (VOT) of AV passengers will decrease and the safety of automobile transport will increase. However, other variables (or driving forces) like vehicle sharing, energy consumption and congestion are very uncertain. It is these uncertain variables that will be used to differentiate among the scenarios. In chapter 4, the AV-related driving forces of residential land use change have been determined. The most uncertain driving force was determined to be 'vehicle ownership structure'. The research question is consequently adapted to this 'key driving force'.

Concluding, the research objective is: To explore and compare the impact of autonomous vehicles and shared autonomous vehicles on the energy-intensity of residential land use. The methodology, the intuitive logics scenario method and system dynamics approach, will be further explained in chapter 3.

First, the research questions will be listed and then they will be further delineated.

Main question

What is the potential impact of privately-owned autonomous vehicles versus shared autonomous vehicles on the energy-intensity of residential land use?

Sub-questions

1. What are the AV-related driving forces of residential land use change?
2. What is the potential impact of privately-owned autonomous vehicles on the energy-intensity of residential land use?
3. What is the potential impact of shared autonomous vehicles on the energy-intensity of residential land use?
4. Which scenario provides the most sustainable land use pattern and how can governments ensure the development of such a scenario?

On the basis of these research questions, the conclusion should answer the question which development is more favourable in terms of environmental sustainability. The use of PAV's or the use of SAV's and why. Consequently, a brief recommendation will be given to ensure the sustainable use of (S)AV's.

Delimitations

- Residential land use is hereby defined as: *"A land use in which housing predominates, as opposed to industrial and commercial areas"* (Definitions.net 2017).
- The term 'energy-intensity' has been chosen because this research is about both the energy consumption of the land use itself and even more about the transportation energy usage that it requires. Energy-intensity thereby corresponds to: *"the total fuel and electrical energy required for material production, transportation, and building operation"* (Norman et al. 2006, p.12).
- Only autonomous passenger transport is taken into account as this is expected to be more directly related to residential land use than freight transport.
- The impact of (S)AV's on residential land use will mainly be discussed in terms of housing density. The diversity and design components of residential land use are expected to be less influenced by transport-related factors, with the exception of parking-space design.
- Sustainable in the context of a 'sustainable land use pattern' in this research refers to the concept of environmental or ecological sustainability. This means that the emphasis of the government recommendations will be on the 'Planet' aspect of the Triple bottom line (3P's). As mentioned earlier, environmental sustainability is indirectly related to residential density.

3 METHODOLOGY

Two main methods will be used to explore the future impact of AV's. The scenario method of intuitive logics will be combined with the system dynamics approach. The intuitive logics scenario method aims to find driving forces, in this case in the context of AV's, that have an impact on "an issue of concern", in this case residential land use. Consequently, scenarios are defined based on the extreme outcomes of the driving forces with the highest degree of impact and uncertainty. These scenarios are then described into more detail in terms of chronological structure and cause and effect relations (Wright et al. 2013; van der Heijden et al. 2002). For this last step, the system dynamics approach will be used to ensure the internal consistency and plausibility of the scenarios. The scenario method is not meant to predict the future but to explore different possible futures in order to stretch conventional thinking.

The system dynamics approach is also known as industrial dynamics and developed by Jay W. Forrester. It is "a body of theory dealing with feedback dynamics. It is an identifiable set of principles governing interactions within systems. It is a view of the nature of structure in purposeful systems" (Forrester 2017 p.401). In other words, it is a way of mapping causal relationships in the form of feedback loops. This mapping process is especially useful for the transport system as this system is characterized by many interacting variables. Fundamental to the system dynamics approach is that *"every influence is both cause and effect, nothing is ever influenced in one direction"* (Haraldsson 2000, p.9). This is also true for the transport system and for the relation between land use and transport which is characterized by interaction. By developing a causal loop diagram (CLD), implications of changes in certain variables will become visible. The causal loop diagram also provides a systematic way to compose a scenario. The system dynamics approach, and more specifically the CLD part of it, has also been applied to asses long term effects of AV's by Gruel &

Stanford 2016. In my thesis, I would like to elaborate on their CLD by adding and altering variables to make the connection with residential land use developments. An example of a CLD composed by Gruel & Stanford 2016 can be found in Figure 13 in the Appendix. The displayed CLD has been slightly simplified by me. The basic structure of this CLD is developed by Sterman (2000).

The CLD by Gruel & Stanford is focused on transport system implications of AV's. Combining this CLD with a residential land use CLD would provide insights into possible implications of AV's for the residential land use system. Examples of CLD's related to (urban) residential density and suburbanization can be found in Chen & Chang 2014, Schwarz et al. 2010, Eskinasi et al. 2009 and Pfaffenbichler et al. 2008.

4 AV-RELATED DRIVING FORCES OF RESIDENTIAL LAND USE CHANGE.

In order to compose scenarios about the impact of AV's on residential land use, the transport-related driving forces that influence residential land use have to be determined. This is the first step of the intuitive logics scenario methodology after setting the agenda (Wright et al. 2013; van der Heijden et al. 2002).

To be able to systematically define driving forces, first the general relation between the transport system and the land use system will be briefly examined. Van Wee et al. 2013 developed a model to elaborate on this relationship. The core of this model is displayed in Figure 2. The model indicates the mutual relationships between the location of activities, including living, the needs and desires of people and transport resistance. Factors included in the needs and desires of people are for example: income, age, sex, household structure and lifestyle (Van Wee et al. 2013). These factors vary between people and are important determinants of individual (residential) location choices. In this study however, the focus will be on the aggregated level and the relation between the transport system and the land use system. Therefore, the individual needs and desires of people are not taken into account in this study. It is assumed that they remain constant on an aggregated level. Besides, non-transport related trends like aging and climate change will not be included in the scenarios as it is uncertain whether they influence residential density at all.

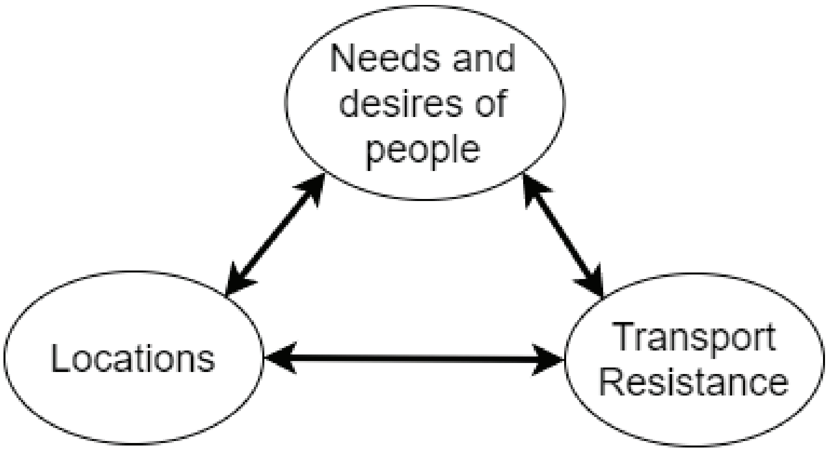

Figure 2: Mutual relationships between transport, location and other factors (Van Wee et al. 2013).

The remaining factor in the model that determines (residential) location choice is transport resistance. This factor includes travel time, monetary costs, comfort, safety and reliability of transport. The sum of these factors is called the generalized transport costs (GTC) in the field of transport economics (Van Wee et al. 2013). The GTC have been related to the phenomenon of 'Urban Sprawl' or low-density suburban development by several authors including Ewing 2008, Christiansen & Loftsgarden 2011 and Squires 2002. It is generally agreed that lower travel costs and higher travel speeds and thus lower GTC, in the long-term lead to lower residential densities. This confirms the relation between transport resistance and location choice.

The factors that make up the GTC will be used to cluster the AV-related driving forces of residential land use change. This process is displayed in Figure 3. The driving forces in the rightmost column are founded on a thorough review of literature on the implications of AV's.

	GTC factors (clusters)	**Driving forces**
Transport resistance	Travel Time	Public/private expenditures on infrastructure
		AV Ownership structure
		AV Cooperative abilities (ACC VS. CACC)
		AV Market penetration rate
		AV Operating speed / Speed regulation
	Travel costs	Public/private expenditures on infrastructure
		AV Ownership structure
		AV Purchase costs
		AV Maintenance & insurance costs
		AV Parking costs
		AV Energy use
	(Dis)comfort	AV VOT / Passenger comfort
	Safety	Safety of AV's
	(Travel time) Reliability	Reliability of AV's

Figure 3: Defining and clustering driving forces of residential land use change related to AV's.

The meanings of most of the driving forces speak for themselves. However, the more difficult and jargon terms are explained in the figure below.

Driving force	**Definition**
AV Ownership structure	Refers to the degree of private AV ownership. Many scenario studies distinguish a transport system based on the use of Shared Autonomous Vehicles (SAV's) and Privately-owned Autonomous Vehicles (PAV's). SAV's are a form of on-demand mobility. The concept of 'mobility as a service' is key to the use of SAV's.
AV Cooperative abilities (ACC VS. CACC)	The ability of AV's to utilize vehicle- to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication to smoothen the traffic flow and decrease the separation distance between vehicles. Adaptive Cruise Control (ACC) vehicles do not have V2V and V2I communication while Cooperative Adaptive Cruise Control (CACC) vehicles do (Fagnant & Kockelman 2015). A CACC dominated system therefore has a higher capacity.

AV Market penetration rate	The extent to which conventional vehicles have been replaced by (S)AV's. The higher the (S)AV penetration rate, the higher the travel time savings because of capacity increases (Fagnant & Kockelman 2015).
AV VOT / Passenger comfort	The Value of Time (VOT) of AV Passengers. This VOT depends on the experienced comfort level and correspondingly the degree of travel enrichment (multitasking while travelling) (Milakis et al. 2016). Lower VOT's probably result in more vehicle kilometres travelled.

Figure 4: Definitions of complicated driving forces.

After the driving forces have been defined and clustered, the next step of the intuitive logics scenario methodology is to define the possible outcomes of each driving force. This step is performed in Figure 5. Additionally, the uncertainty of each driving force is indicated according to the currently available scientific literature. The degree of uncertainty will be used to compose an impact-uncertainty matrix in the next step.

Driving force	**Possible Outcomes**	**Comments on uncertainty**	**Source(s)**
Public/private expenditures on infrastructure	High or low expenditures, public or private expenditures	The need for conventional road infrastructure investments (extra-wide lanes, wide shoulders, guardrails, rumble strips, stop signs) is reduced[1,2]. However, new investments in physical and digital infrastructure for AV's may be necessary, communication infrastructure is highly costly[1,2].	[1] (Milakis et al. 2017) [2] (Silberg & Wallace 2012)
AV Ownership Structure	PAV dominated or SAV dominated	Very uncertain. Car ownership could increase due to the increased usefulness of cars. On the other hand, car ownership could decrease because it will be easier to share cars[1]. Some authors claim that the preference for car-sharing is growing[2,3]. Others mention that *"studies on actual trends on car use and ownership do not suggest the* (private) *automobile losing its predominance at present"* [4].	[1](Papa & Lauwers 2015) [2](Alessandrini et al. 2015) [3] (Ohnemus & Perl 2016) [4] (Fraedrich et al. 2015, p.4)
AV Cooperative abilities (ACC VS. CACC)	Increases over time, CACC will eventually become the standard	*"Vehicle communication is likely to become standard on most vehicles before significant proliferation of AV capabilities throughout the U.S. vehicle fleet"*[1]	[1] (Fagnant & Kockelman 2015)
AV Market Penetration	Increases over time, rate is unknown	Depending on the degree of technological development and the AV policy context, a penetration rate between 7% and 61% is expected in 2050[1]. Alessandrini et al. 2015 claims that market penetration is complete in 2060.	[1] (Milakis et al. 2017)
AV Operating speed / speed regulation	Operating speed is likely to increase, speed regulation consequences are unknown	Since human attention and reaction times are no longer limiting operating speed[1], it is likely to increase. However, this means an increase in energy usage[1] and more induced demand[2] so speed regulation will probably limit operating speed.	[1] (Wadud et al. 2016) [2] (Papa & Lauwers 2015)
AV Purchasing costs	Extra technology costs, decreases with market penetration	Purchase costs will be higher than the price of conventional vehicles due to technology costs[1]. The extra costs will decrease with market penetration rate because of economies of scale.	[1] (Fagnant & Kockelman 2015)

AV Maintenance & insurance costs	Insurance costs decrease to an unknown extent. Maintenance costs increase to an unknown extent	Insurance costs decrease due to safer traffic operations[1]. Maintenance costs are expected to increase because of the technological complexity of AV's[2]	[1] (Wadud et al. 2016) [2] (Heinrichs 2015)
AV Parking Costs	Decreases to an unknown extent	In the case of a SAV dominated mobility system, parking demand decreases up to 90%[1]. This in combination with the possibility to move vehicles out of higher-priced parking spots[2] can lead to significantly lower parking costs.	[1] (Zhang et al. 2015) [2] (Fagnant & Kockelman 2014)
AV Energy Use	Seems likely to decrease per km but total energy usage is unknown	Fuel economy will be improved by smoother (de)acceleration, lighter vehicles and platooning[1]. However, increased travel demand can possibly outweigh the achieved energy savings[1].	[1] (Anderson et al. 2014)
AV VOT \ passenger comfort	Comfort increases and VOT decreases to an unknown extent	An increase of vehicle kilometres travelled is expected as a result of a decrease of the VOT[1,2]. The extent to which VOT decreases hasn't been researched yet and can vary greatly.	[1](Gucwa 2014) [2] (Milakis et al. 2016)
Safety of AV's	Safer than human drivers, however new risks like hacking can emerge.	Since 94% off all crashes are mainly caused by driver error[1], motor-vehicle fatality rates are certainly expected to decrease significantly (up to 1% of current rates[2]). Rebound effects can lower this increased safety somewhat.[3]	[1] (Singh 2015) [2] (Hayes 2011) [3] (Alessandrini et al. 2015)
Reliability of AV's	Is expected to increase but demand and congestion feedback can lower reliability	*"The combination of smoother flowers and more useful travel information could also increase the predictability and reliability of trips"* [1]. Congestion as a result of increased demand however does the opposite.	[1](Smith 2012, p.1413)

Figure 5: Possible outcomes and uncertainties of driving forces

Hereafter, the driving forces will be placed in an impact-uncertainty matrix (see Figure 6). This matrix is essential in determining the key scenario driver. This is the driver with the highest degree of uncertainty and the highest degree of impact on residential land use. The degree of uncertainty is largely based on scientific qualitative and quantitative literature while the degree of impact is purely based on intuitive logics. This is because there is hardly any available scientific literature that indicates the relation between the driving forces and (residential) land use. However, one can reason that driving forces that have an impact on both travel time and travel costs have a higher impact on residential land use than driving forces that only affect one of the components of GTC. This is why AV ownership structure and infrastructure expenditures are placed as high impact driving forces. Furthermore, driving forces that affect travel time, which is directly related to travel distance, are considered to have a higher impact on residential land use than driving forces that affect other components of GTC. The reason for this is that travel time has often directly been linked to accessibility (Hansen 1959; Meyer et al. 2017). The other components of GTC have a less strong and clear relationship with accessibility. Accessibility in turn affects residential location choice because a higher degree of accessibility leads to more dispersed residential development (Wegener & Fuerst 1999).

The key scenario driver that can be derived from the impact-uncertainty matrix is AV Ownership structure. This driver is also assumed to be highly uncertain and influential by other (scenario) studies about autonomous vehicles, some very focused (Meyer et al. 2017; Haboucha et al. 2017) and some general (Fraedrich et al. 2015; Gruel & Stanford 2016b). The reason for the high uncertainty of the variable 'vehicle sharing' is that it involves behavioural aspects in addition to technical and economic aspects. Other variables like cooperative abilities, safety and infrastructure depend more on technical developments. These technical developments, although the time-aspect of them is very uncertain, have a more predictable character than travel behaviour.

The two extreme, yet plausible outcomes of 'AV Ownership Structure' are a PAV dominated mobility system or a SAV dominated mobility system. These outcomes will form the basis of the two corresponding scenarios that will be developed in the next chapter. The remaining driving forces will also be incorporated into the scenario plots. The driving forces with a low degree of uncertainty will shape the circumstances within the scenarios. The outcome of the more uncertain driving forces will be determined by their consistency with the key scenario driver. This procedure is in line with the intuitive logics method (van der Heijden et al. 2002).

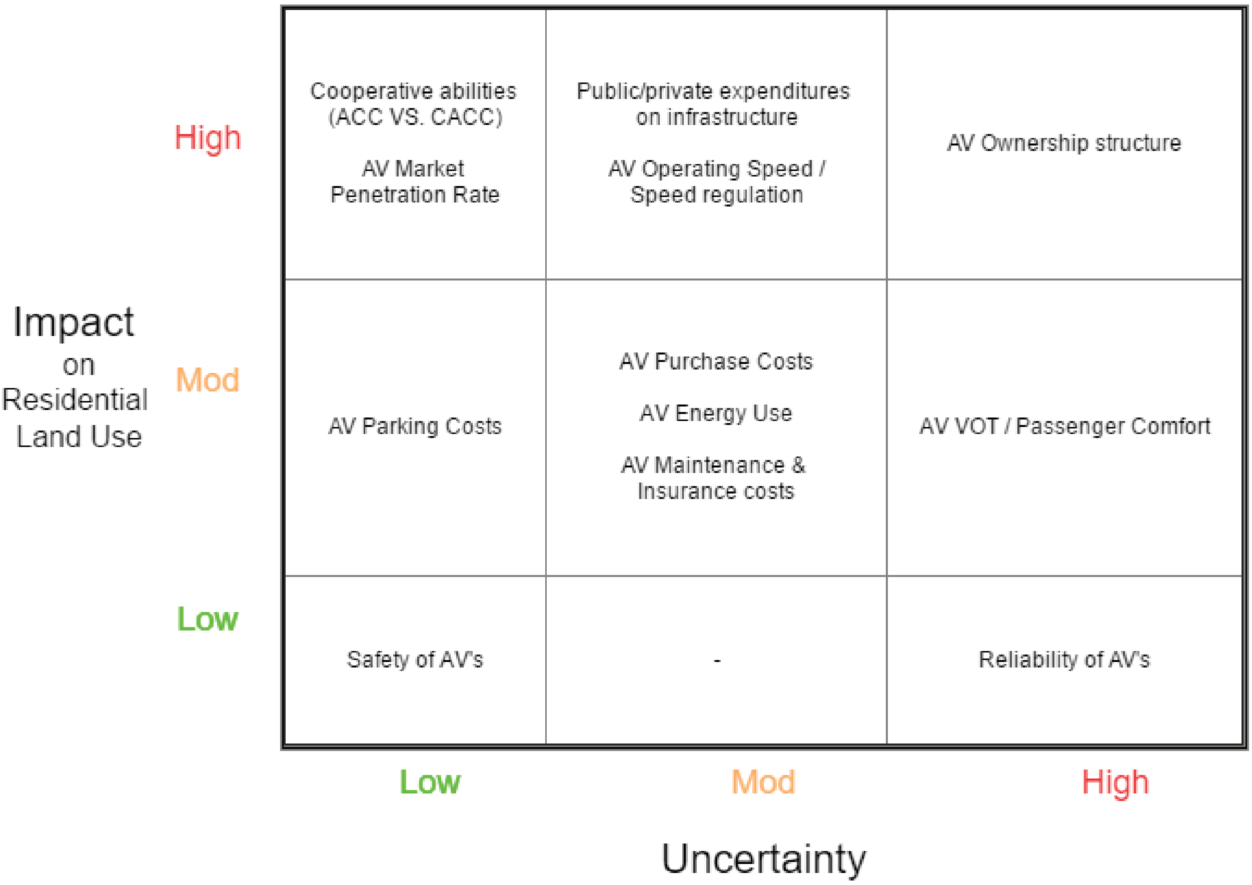

Figure 6: Impact-Uncertainty Matrix

5 THE IMPACT OF AUTONOMOUS VEHICLES ON RESIDENTIAL LAND USE

In this chapter, two scenarios will be plotted. One scenario where Privately-owned Autonomous Vehicles (PAV's) have come to dominate the mobility system and one where Shared Autonomous vehicles (SAV's) have done so. In both of the scenarios, AV's have replaced most of the conventional vehicles and thereby achieved a market penetration rate of at least 50%. This means that the scenario time frame is the year 2050 and later (Milakis et al. 2017). The reason for starting from a high market penetration rate is that he level of uncertainty of the market penetration of AV's is relatively low, as argued in the previous chapter.

Before the specific scenarios will be plotted, first the scenario baseline will be described. This scenario baseline contains the future conditions that are true for both AV and SAV dominated mobility systems. Therefore, the driving forces of the scenario baseline are called 'general AV-related driving forces'. Later in this chapter, the scenario-specific conditions will be elaborated on.

5.1 SCENARIO BASELINE

The scenario baseline forms the basis of both of the scenarios that will be described further on. It contains a description of general AV-related driving forces and a basic causal loop diagram.

5.1.1 GENERAL AV-RELATED DRIVING FORCES

The introduction of AV's first of all significantly increases the target market for personal automobile transport since people that were unable to drive can now drive as well. A driving license is no longer necessary for fully automated vehicles. The new target group includes younger people, older people and those with disabilities (Silberg & Wallace 2012). At this moment, approximately 64% of the Dutch population has a driver's license (CBS 2017). This means that the Dutch automobile target market can potentially expand with 36%. Poverty however will remain as a barrier (Smith 2012). In addition to more potential car users, a decrease of transport resistance is expected as a result of the increased comfort and travel time enrichment AV's offer. Travel time in AV's can for example be used for working, relaxing, eating and sleeping (Haboucha et al. 2017). The increase of travel demand that results from this is estimated to be between 3% and 27% (Milakis et al. 2015). This increase in Vehicle Kilometres Travelled (VKT) is related to a decrease in personal Value Of Time (VOT) because the travel time can now be used more effectively. The decrease in VOT is expected to be the same for PAV's and SAV's (Fagnant & Kockelman 2015).

Not only the usability advantages AV's bring reduce transport resistance, further travel cost and travel time benefits can be realised. High-tech AV technologies and cooperative AV technologies offer the possibility of platooning whereby the distance between vehicles is significantly reduced. This increases the capacity of roads and thereby reduces the risk of congestion (= increased travel time). On top of that, energy costs of vehicles can be reduced because platooning lowers the amount of drag. This allows for a decrease in the energy intensity of vehicles from about 3% up to 25% (Wadud et al. 2016). The technology that enables platooning also makes safe driving at higher speeds possible. The maximum operating speed is thereby no longer limited by human perception and reaction times (Wadud et al. 2016). Higher travel speeds mean less travel time and a lower transport resistance. This effect is slightly counteracted by the higher energy intensity (and higher travel costs) of higher operating speeds (Wadud et al. 2016).

Another factor that decreases transport resistance and thereby increases VKT is the improved safety of AV's. *"A huge reduction of road accident fatalities and crashes is expected"* (Alessandrini et al. 2015, p.157). This not only diminishes psychological barriers to car travel but also increases the capacity of the road networks and improves the travel time reliability of car travel. On top of that, safer vehicle operations allow for the usage of lighter vehicles (without structural steel, roll cages etc.) which are less energy intensive (Forrest & Konca 2007). Travel cost benefits other than lower energy costs can be realized by the avoidance of expensive parking. AV's will eventually have the ability to autonomously find a parking spot, with or without passengers. An empty vehicle trip to find a parking spot after one or more passengers have been disembarked is called a zero-occupant ride (Ohnemus & Perl 2016).The ability to autonomously find a parking spot is called Valet Parking (Hayes 2011). Parking outside of higher-priced parking areas can significantly reduce travel costs. (Greenblatt & Shaheen 2015). This is especially true for trips to urban centre areas. Parking costs are further reduced by the more efficient use of parking areas. With Valet parking, cars can be parked closer together since door access is no longer necessary. Parking space savings are even higher for SAV's, this will be further explained in chapter 5.3. The elimination of parking hassle is another psychological factor that can increase AV travel demand (Hayes 2011). Travel cost savings as a result of cheaper parking are partly neutralized by the higher purchasing costs of AV's. These extra costs are due to the expensive technology that enables autonomous driving and cooperative driving (Milakis et al. 2015). The way these costs are experienced by the consumer differs per scenario. Despite the higher purchasing costs of AV's, the cost savings of parking, energy and time are expected to outweigh the extra costs in the long term (Fagnant & Kockelman 2015; Smith 2012). Al these factors and the factors mentioned earlier in this chapter significantly reduce transport resistance.

Now that the AV-related driving forces that lower transport resistance and thereby cause suburbanization have been discussed, the counteracting forces will be described. A lower transport resistance induces more travel demand which results in higher traffic volumes (Van Wee et al. 2013). Other AV-related factors that increase the traffic volume are AV mobility for those unable to drive and the occurrence of zero-occupant rides. Higher traffic volumes then increase the probability of congestion. Congestion increases the transport resistance because of longer travel times and less travel time reliability. A decrease in reliability means more uncontrollable time-loss and this is a major cause for travel stress (Heinrichs 2015). This means that congestion can possibly counteract suburbanisation. However, AV technologies under which CACC can increase the capacity of especially freeways (Fagnant & Kockelman 2015). The capacity increase is estimated to be large enough to adequately accommodate the induced travel demand (Forrest & Konca 2007). Even when the VKT doubles, improvements in safety should be sufficient to not let congestion occurrence increase (Fagnant & Kockelman 2015). On top of that, investments in new infrastructure are able to reduce or prevent congestion when it does occur. The only area where congestion may increases is on arterial roads (Fagnant & Kockelman 2015). Overall, the 'congestion force' isn't likely to be strong enough to counteract suburbanisation on the long term. Other factors that can possibly counteract suburbanisation are land use regulations and economic reforms that address market failure. These are however internal forces to governments and are irrelevant to (external) scenarios. The consequences of the overall decrease in transport resistance, in addition to more scenario-specific factors, will be described in chapters 5.2 and 5.3. First, the system dynamics methodology will be applied to organize the just mentioned driving forces.

5.1.2 CAUSAL LOOP DIAGRAM

In Figure 7 a causal loop diagram (CLD) is displayed that relates all of the abovementioned general driving forces to transport resistance, suburbanization and energy consumption. The CLD is partly based on the one developed by Gruel & Stanford 2016a. However, the basic model has been severely altered to describe the relation between the transport system and residential (sub)urbanization more accurately. Whereas the model by Gruel & Stanford 2016a only uses the variable 'Size of region within acceptable travel time' to explain urban sprawl, this model relates all the factors of transport resistance to residential suburbanization.

It must be noted that this 'scenario baseline model' only indicates causal relations that have an impact on residential suburbanization and energy consumption. The feedback relations that result from suburbanization are not included in this model. These will be extensively covered in the latter part of this chapter where the specific scenarios are plotted.

The CLD in Figure 7 consist of different elements. The driving forces in the upper part of the diagram are color-coded according to their impact on residential land use (see diagram legend). The factors that together form transport resistance are boxed and are displayed on one horizontal line. General variables are in black, the main variables of transport resistance and residential suburbanization are black bold and boxed. The black variables are so-called endogenous variables. These variables are interactive within the system while the driving forces only influence the system (Haraldsson 2000). Arrows indicate causal relationships. A + sign near the arrowhead means that the variables are moving in the same direction (Haraldsson 2000). For example, when traffic volumes increase, congestion also increases. A – sign on the other hand means that the variables are changing in the opposite direction (Haraldsson 2000). For example, when road capacity increases, congestion decreases. Another sign in the diagram is the delay mark which is a double line that crosses the arrow. A delay mark indicates that it takes time before a causal relationship takes place. For example, it takes a while before a lowered transport resistance manifests itself in the form of residential suburbanization.

From the CLD and the scenario baseline, one can conclude that AV's are likely to shift the residential land use system towards a more dispersed pattern. However, the driving force with the highest degree of impact and uncertainty, namely vehicle ownership structure, has not yet been taken into account. This will happen in the next section where two scenarios are plotted based on the extreme outcomes of this driving force.

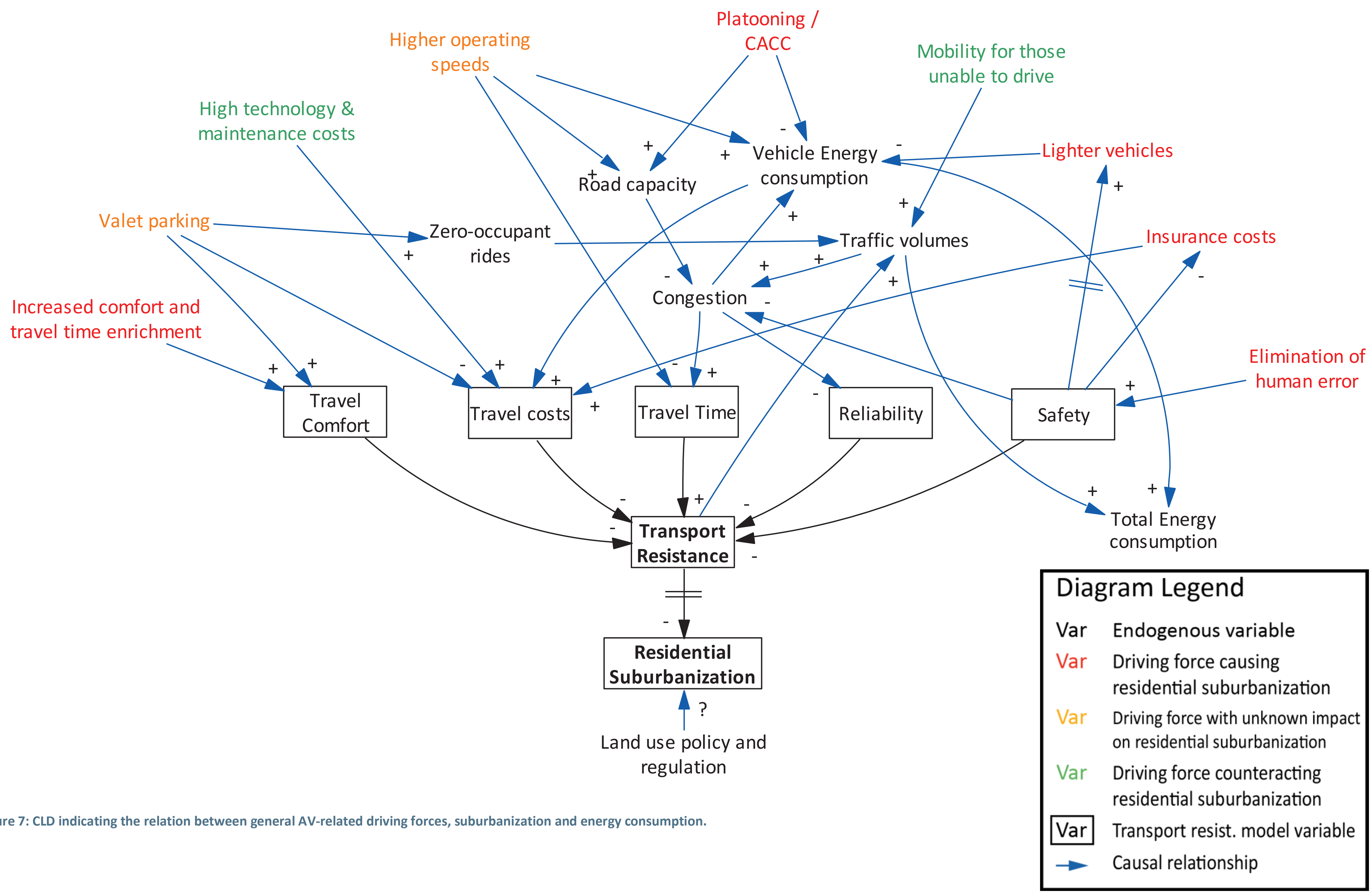

Figure 7: CLD indicating the relation between general AV-related driving forces, suburbanization and energy consumption.

5.2 SCENARIO 1: PRIVATELY-OWNED AUTONOMOUS VEHICLES

This scenario is based on a dominant usage of PAV's. The ownership structure of vehicles has therewith remained the same. However, travel behaviour and land use are expected to change as a result of the usage of PAV's. The driving forces of these changes are explained first. Thereafter, all of the driving forces will be linked in a causal loop diagram.

5.2.1 PAV-RELATED DRIVING FORCES

Besides the general AV-related forces that have an impact on transport resistance, there are some additional forces that are specific to Privately-owned AV's (PAV's). One of them is the extensive occurrence of zero-occupant rides. Fully automated AV's can drive with or without passengers. This way, one AV can be used to service the whole family (Forrest & Konca 2007). Different family members with partly overlapping time schedules can use the same AV, thereby reducing the need for expensive parking. This works with a function called "return-to-home" mode (Schoettle & Sivak 2015). This situation is unique for this scenario. The occurrence of zero-occupant rides leads to higher numbers of VKT (Schoettle & Sivak 2015). Zero-occupant rides are therefore costly since the variable ride costs (e.g. energy and maintenance costs) will remain. On top of that, the environmental impact of the inefficient zero-occupant rides is high. However, family car sharing does make it possible to reduce vehicle ownership per household. Schoettle & Sivak 2015 have found that in the most extreme scenario, the average vehicle ownership rates can be reduced from 2,1 to 1,2 vehicles per household. As a result, individual vehicle usage increases by as much as 75%, not including the return-to-home trips (Schoettle & Sivak 2015; Johnson 2015). A reduced number of owned vehicles per household means that the fixed costs (depreciation, insurance, taxes etc.) of car travel, which make up a significant part of the total costs (Wadud et al. 2016), can be greatly reduced. This in turn reduces transport resistance.

The amount of induced travel demand (which depends on the transport resistance) seems to be strongly related to vehicle ownership structure. Substantial increases in travel demand are expected for scenarios with PAV dominated mobility. The travel demand in scenarios with SAV dominated mobility is estimated to be the same or lower than it is now (Childress et al. 2015). This difference can be attributed to the pricing structure of both scenario's (Levinson 2015). In the case of SAV's, travellers are subject to full marginal-cost pricing (Wadud et al. 2016). However, in the case of PAV's, customers pay the purchasing price of an AV once and consequently are less likely to consider the full price of each trip. In fact, PAV's encourage the making of more and longer trips since the per-kilometre-costs will then decrease. After all, the fixed costs can be spread out over all of the VKT. This also has a negative impact on conventional public transport (from now on: public transport) usage since the public transport ticket price is based on marginal pricing instead. Prettenthaler & Steininger 1999 describe this discrepancy as follows: *"With private car ownership, once the fixed costs have been paid, they are correctly regarded as sunk costs. The remaining variable cost component often is lower than, for example, public transport fares on an average cost basis, which induces car use"* (Prettenthaler & Steininger 1999, p.445).

5.2.2 RESIDENTIAL LAND USE IMPLICATIONS

In the end, the use of PAV's in specific seems to decrease transport resistance even further. This would imply a similarly large dispersion trend of residential housing (Hayes 2011; Ohnemus & Perl 2016). Levinson 2015 argues that *"Historically, every increase in mobility (such as the ability to go faster, either due to new technologies or more connected networks) has increased the size of metropolitan areas"* (Levinson 2015, p.803). This trend of suburbanization can be fed by different other factors. First of all, land-prices tend to be lower in lower density areas outside of the city since less pressure on housing results in lower housing prices (Christiansen & Loftsgarden 2011). This also means that for the same price, a larger house can be bought in low density areas than in high density areas (Levinson 2015). Secondly, there is a tendency towards living in (rural) green areas based on individual preferences. Especially young couples with children rather live further away from the city centre and have access to a garden than the other way around (Christiansen & Loftsgarden 2011). The reason for this is that: *"working people's choice of where to live is far more influenced by factors such as quality of life and living environment than the wish to be near to their place of work"* (Heinrichs & Cyganski 2015, p.77). Finally, the revolution of ICT technology, which is in some ways related to the development of AV's, enables footloose working and working at home. The agglomeration benefits for people have therewith decreased (Audirac 2005). The interplay of all these factors in combination with a decrease in transport resistance lead to a tendency towards suburbanization. Whether this suburbanization manifests itself into the physical landscape depends on land use policies and regulations (Milakis et al. 2015). This research however focuses on the external suburbanization force itself. One could argue that despite of land use regulations, the suburbanization tendency will sooner or later shape land use in some way.

An important function of the usage of scenarios is the 'stretching' of conventional thinking (Xiang & Clarke 2003). To achieve this Xiang & Clarke 2003 argue that, among other factors, the information vividness of scenarios is very important. The usage of imagery increases this information vividness. However, at the highly aggregated level of this scenario study, detailed and speculative imagery would infringe upon the scientific credibility of the scenarios. Therefore, an abstract yet vivid city model will be used to illustrate the spatial implications of the scenarios. The PAV-scenario model can be found in Figure 8. The model is an alteration of the well-known concentric zone model by Ernest Burgess. It should be taken into account that this model is an extreme simplification of real urban land use patterns. However, the basic structures of many cities show similarities with the model.

A concentric city model was chosen because it *"represents the most common morphological form in the Netherlands"* (Snellen et al. 2002, p.1211). The residential density in this model decreases with the distance to the CBD. The public transport network has a radial form, which is also common in the Netherlands (Snellen et al. 2002). For road networks, the ring is more often applied, usually around the CBD (Snellen et al. 2002). The model also indicates the main traffic flow which is to and from the CBD. The thickness of the depicted infrastructural networks is indicative for its usage. When compared to scenario 2, road networks inside of the city are more dominant in this scenario. New low density residential developments are expected at the edge of the city near the main infrastructural spokes (provided they are locally accessible). Christiansen & Loftsgarden 2011 argue that an increased availability of infrastructure contributes to new areas becoming attractive for residential (and other) developments. Besides that, investments in new infrastructure can be minimized when developments are located near existing infrastructure. The main picture that arises out of this model is that of an expanding city.

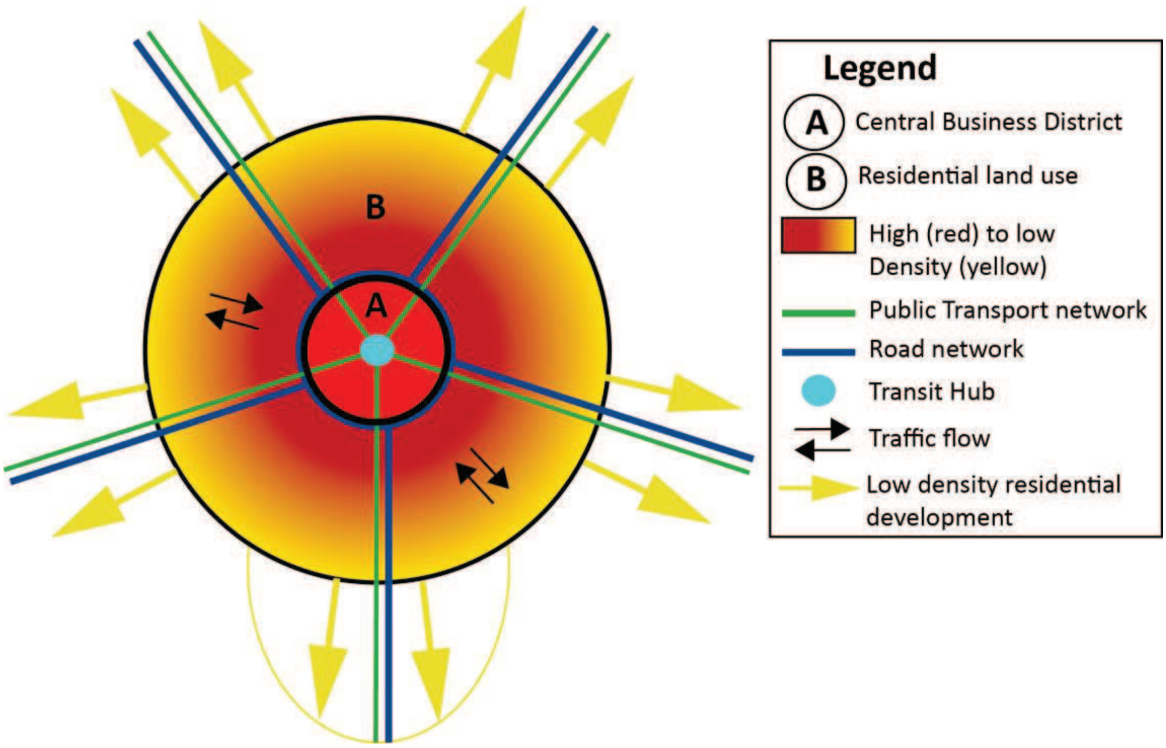

Figure 8: City model illustrating the implications of PAV's for residential land use and transport

5.2.3 CAUSAL LOOP DIAGRAM & FEEDBACK LOOPS

The relations between the driving forces that have been described in both the scenario baseline and the PAV scenario are schematically displayed in Figure 9. For reasons of clarity, the scenario baseline variables that are not affected in this scenario are made a little transparent. The causal loop diagram (CLD) in Figure 9 also features the non-transport related driving forces of suburbanization that have been described above.

Generally said, the factors influencing transport resistance are in the upper part of the diagram and the consequences of changes in transport resistance are in the lower part of the diagram. The CLD exposes a number of feedback loops that are important in determining the environmental consequences of the use of PAV's. The most important feedback loops will be discussed below.

Suburbanization from an environmental point of view is, in many ways, problematic. This has to do with the feedback loops that cause an increase in energy usage. First, *"Higher densities mean shorter trips and more travel by energy-conserving modes"* (Ewing 2008, p.528). Low densities on the other hand lead to longer trip lengths and more car dependency (US EPA 2001). Second, the adequacy of public transport decreases as the dispersion of origins and destinations increases (Gruel & Stanford 2016b). The dispersion of origins and destinations is linked to suburbanization. Public transport relies on the aggregation of people by space and time. Therefore, *"Public transit in low-density areas offers* *mobility that is often slow and unreliable"* (Ohnemus & Perl 2016, p.597). Finally, low-density residential buildings, which are often detached single-family houses, use approximately twice as much energy per capita as multiunit buildings (terraced houses and apartments) (Norman et al. 2006). Reasons for this are the higher exterior wall surface area of detached houses, their inefficient use of building materials and their higher energy use in terms of building operations (Norman et al. 2006). The overall feedback that results from residential suburbanization which is consequently caused by PAV mobility is therefore an increase in total energy consumption (see Figure 9).

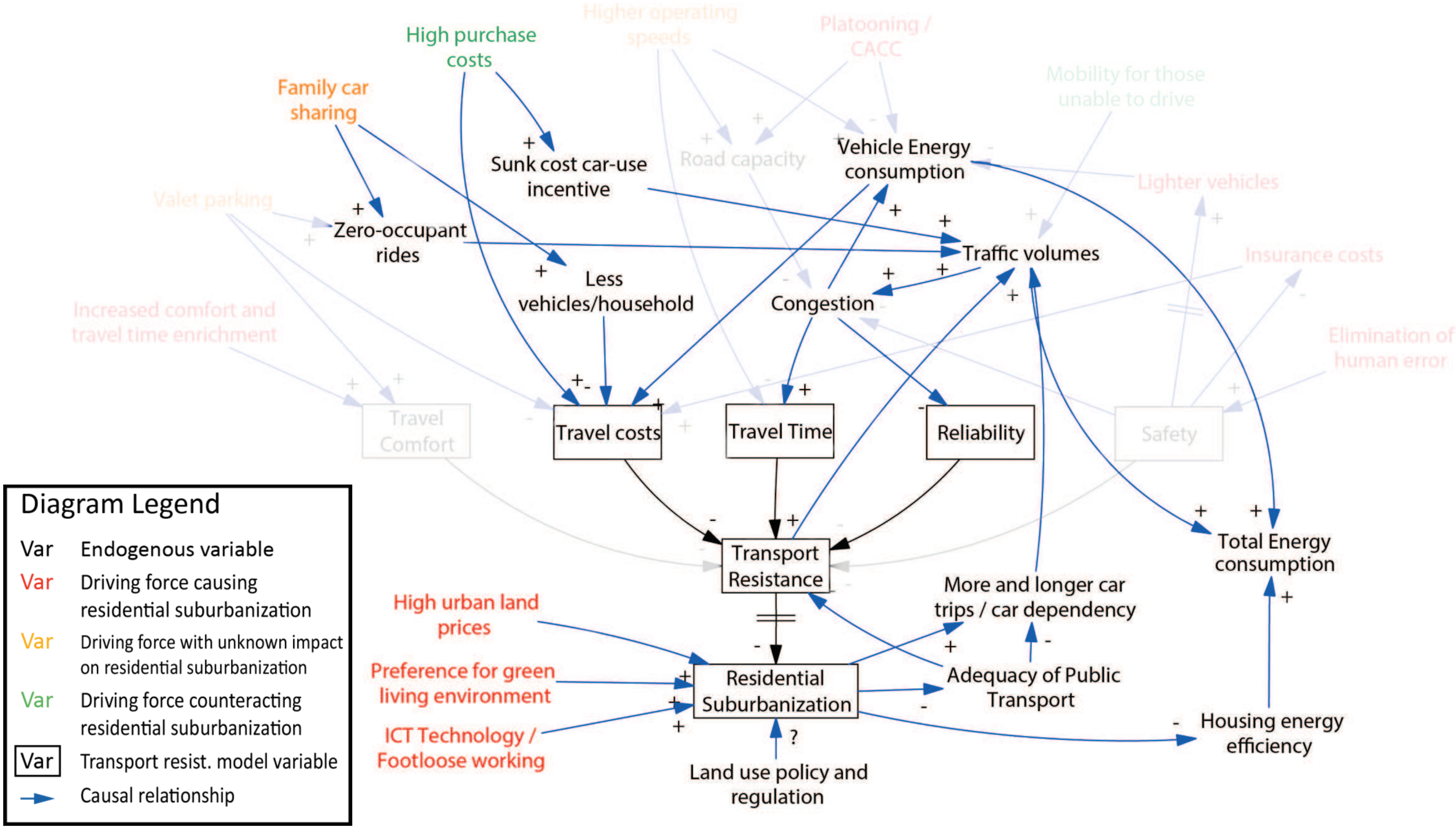

Figure 9: CLD indicating the relation between PAV driving forces, suburbanization and energy consumption.

5.3 SCENARIO 2: SHARED AUTONOMOUS VEHICLES

This scenario describes the environmental and residential land use implications of the use of Shared Autonomous Vehicles (SAV's). SAV's are not privately-owned but are owned collectively through a car sharing organization. Members of this organization can use any of the shared vehicles based on availability. An SAV trip first has to be 'booked' via, for example, an App. The SAV will then be deployed accordingly. This concept is also called 'mobility as a service'. Trips are charged based on usage time and VKT (Prettenthaler & Steininger 1999). In other words, SAV users are subject to full marginal-pricing.

5.3.1 SAV-RELATED DRIVING FORCES

The widespread usage of SAV's has a number of environmental benefits as opposed to the usage of PAV's. First of all, vehicle ownership can dramatically decrease when SAV's are widely used. Each SAV is namely able to replace 9 to 13 privately-owned vehicles (Greenblatt & Shaheen 2015). Johnson 2015 even speaks of 9 to 18 vehicles when not only vehicles but also rides are being shared. A reduced rate of vehicle ownership not only means that less construction resources are needed. It is also associated with a modal shift towards more energy-conserving modes of transport such as walking, cycling and public transport (Greenblatt & Shaheen 2015; Childress et al. 2015). On top of that, a decrease in VKT per person is expected (Greenblatt & Shaheen 2015) while an increase in VKT per vehicle is a likely outcome (Wadud et al. 2016). A higher number of VKT per vehicle is favourable because high energy costs in relation to (financed) capital costs result in an incentive towards more energy-efficient vehicles (Greenblatt & Shaheen 2015; Wadud et al. 2016). The reason for this is that the higher capital costs of high-tech energy-efficient vehicles can be more easily earned back by achieved energy-savings. Another benefit of the usage of SAV's is that the space required for vehicle parking decreases tremendously (Alessandrini et al. 2015). In addition, up to 90% of the parking demand itself can be eliminated (Zhang et al. 2015). Space savings are therefore even higher than those in scenario 1 where Valet parking is also possible. The implications of the usage of SAV's will be described into more detail further down. Now, the consumer-related benefits of SAV's will be discussed, these ultimately determine whether SAV's or PAV's will become dominant.

SAV's are attractive for people that want to reduce their fixed vehicle costs as trade-off for more variable costs. This is especially true for people that irregularly use a car. SAV's alleviate the conventional car hassle in terms of insurance, repairs, maintenance and other responsibilities (Prettenthaler & Steininger 1999). They are therefore also a good alternative for regular car users. Furthermore, shared car users are provided with more flexibility in terms of the type of car they use. Differently sized cars can be used according to the purpose of one's trip (Levinson 2015). When smaller and lighter vehicles are being used for trips with one or two passengers, the average energy consumption of the fleet can be reduced by as much as a factor of two (Greenblatt & Shaheen 2015).

SAV's can also be a cheaper alternative to PAV's for customers who drive average to low distances per year. The breakeven point of a privately-owned car depends on a lot of factors. To give an indication, Prettenthaler & Steininger 1999 argue that the breakeven point of a private car is 15.000 kilometres per year. This would mean that shared cars are a cheaper alternative for all car users that drive less than 15.000 kilometres per year. However, the costs per kilometre are not the only criteria for car users to decide on vehicle ownership. Waiting time (and costs), convenience and prestige are other crucial factors that determine the attractiveness of SAV's (Prettenthaler & Steininger 1999). When compared to contemporary car sharing services, SAV's have the advantage that they do not have to be picked up and delivered to a certain location since they can drive autonomously (Greenblatt & Shaheen 2015).

The pricing structure of SAV's is the main reason that the VKT of SAV passengers is expected to be lower than those of PAV users. The price of SAV trips is fully transparent as opposed to the price of PAV trips. The SAV trip price consists of energy costs, parking costs, vehicle and infrastructure maintenance costs, vehicle purchasing costs and other costs of negative externalities (Childress et al. 2015). SAV users pay this price per journey and are therefore more likely to travel efficiently and maybe share a ride (Ohnemus & Perl 2016). Moreover, to save trip costs, SAV users can transfer to public transport lines for the major leg of the trip and use the SAV as a "first- and last-mile solution" only (Ohnemus & Perl 2016). The SAV's are hereby used as feeders and distributors for public transport lines. This way, an integral transport network based on intelligent combinations of modes is being formed (Alessandrini et al. 2015). From an environmental point of view, this is very favourable since public transport is way more energy efficient per passenger than automobiles are (Norman et al. 2006). SAV's are also able to improve the public transport network by offering (better) connectivity to low density/demand areas that cannot be served by conventional public transport lines (Ohnemus & Perl 2016). In short, *"SAVs would make intermodal journeys even more attractive, through merging the flexibility of motor vehicles with the cost efficiency of collective transportation"* (Ohnemus & Perl 2016, p.598). Parking problems that exist today at transferring stations can also be mitigated by the usage of SAV's since local parking is often not necessary. Instead, SAV's will continue to service passengers (Heinrichs 2015).

Although SAV's are capable of replacing public transport in low density/demand areas, they are not able to replace public transport in high density urban areas. Here, the travel demand would far outweigh the capacity of SAV's even though this capacity is higher than that of conventional vehicles (Meyer et al. 2017; Lauwers 2015).

At times of low demand or unbalanced demand, SAV's may need to park themselves to ensure cost- and energy-efficient operation. The space needed to park an SAV is about one quarter of the space needed to park a conventional vehicle (Alessandrini et al. 2015). The reason for this is that both door accessibility and individual vehicle accessibility are not necessary in the case of SAV's. This is illustrated in Figure 10 by Alessandrini et al. 2015. Less required parking space also means that parking costs can be lower for SAV's.

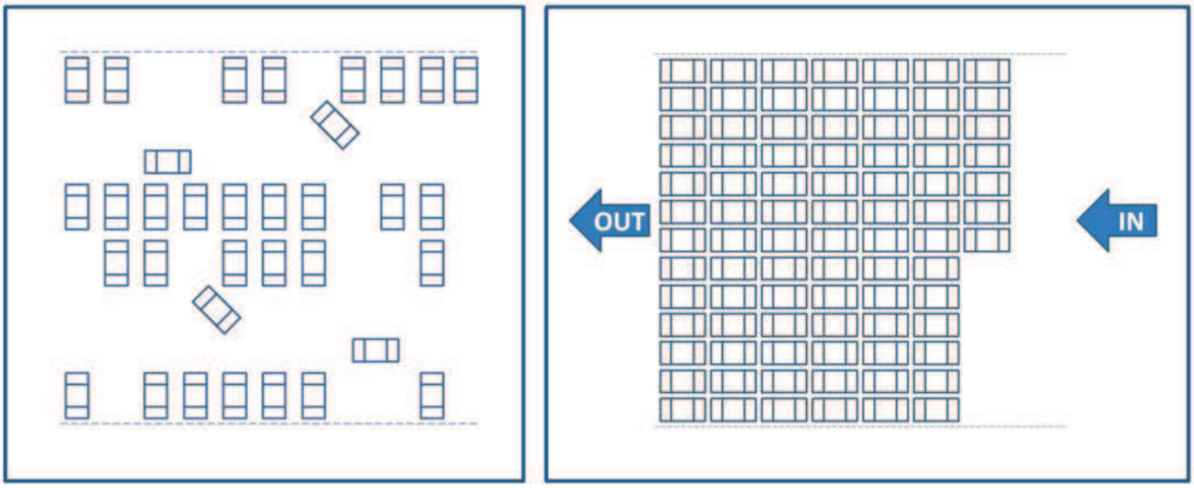

Figure 10: Space required to park conventional vehicles (left) versus SAV's (right) (Alessandrini et al. 2015).

Just like the PAV scenario, SAV's will facilitate the occurrence of zero-occupant rides. There is however a critical difference with scenario 1. Individual SAV's have a way larger customer base. This means that the number of VKT with zero passengers can be minimized. The central 'booking system' is able to assign passengers to the nearest available vehicle and if desirable form groups of passengers with similar destinations. Since SAV's need communication technology to enable this dynamic ridesharing, it is more likely that SAV's will also be equipped with V2V and V2I communication. Another reason why advanced communication techniques are easier to implement is that SAV's are owned by large organizations instead of countless individuals. This brings CACC a step closer as compared to scenario 1. CACC is able to significantly increase the capacity of roads (Milakis et al. 2016) but CACC infrastructure is also a way more expensive than conventional infrastructure (Silberg & Wallace 2012). Therefore, investments in new infrastructure are less likely in this scenario, investments in the upgrading of existing infrastructure are on the other hand more likely.

In the end, the usage of SAV's could decrease the current VKT and vehicle hours travelled per person by as much as 20% to 30% (Childress et al. 2015). Along with a decrease in vehicle ownership, the greenhouse gas emissions of households can be reduced with 34% to 41% (Greenblatt & Shaheen 2015). These numbers were found in a study of multiple North American cities where 9635 surveys on car sharing were conducted. The results for Europe and The Netherlands can deviate from these numbers but it is clear that SAV's do not substantially reduce (car) transport resistance and thereby induce more VKT.

5.3.2 RESIDENTIAL LAND USE IMPLICATIONS

The non-transport related factors that cause suburbanization, which are mentioned in scenario 1, also apply in this scenario. However, the other essential condition that feeds suburbanization namely, a lower transport resistance, is not applicable to the same extent in this scenario. This means that suburbanization will be more limited in this scenario than in scenario 1. There are however other notable changes in residential land use. The possible reduction in parking space provides opportunities for spatial transformations. Within city centres and to a lesser degree outside of city centres, almost all parking places, with the exception of cargo supply spots, can be eliminated. Instead, SAV's that are idling can be parked concentrated in large scale parking facilities on less valuable land. These facilities also allow for cost-efficient cleaning, energy-charging and maintenance (Heinrichs 2015). According to Zakharenko 2016 about 97% of the parking demand can shift to these peripheral parking facilities. This would mean a huge increase in available urban land. Townsend 2014 mentions that as much as 50% of the land in American cities is now used for parking and can be redeveloped.

The space formerly occupied with parking places can be used for three possible purposes. One is the reinforcement of transport and recreational networks such as public transport, bicycle and pedestrian networks (Heinrichs 2015; Townsend 2014). This can strengthen the modal shift towards energy-conserving modes even more. Another purpose is to upgrade public space by adding green park-like elements and street furniture. This has the potential to improve the health and wellbeing of urban residents (US EPA 2001). A final purpose is to increase residential density and/or commercial density. As mentioned earlier, higher densities favour the use of public transport, walking and cycling and are therefore more energy-efficient (Balcombe et al. 2004; US EPA 2001). On top of that, higher residential densities may also result in less energy usage by automobiles since travel distances are shorter (Balcombe et al. 2004) and the fleet tends to be more energy-efficient (Brownstone & Golob 2009).

Additionally, more available urban land, in other words more land supply, also results in lower rent prices (Zakharenko 2016) which counteracts the land-price related suburbanization factor introduced in scenario 1. Zakharenko 2016 argues that the Central Business District (CBD) of cities will become smaller because they can be more concentrated due to the removal of parking spaces (this is displayed in Figure 11). Heinrichs 2015 in his scenario study also speaks of highly concentrated CBD's. This has a positive influence on the productivity of CBD's (Zakharenko 2016). On top of that, economic activity is expected to be drawn from the periphery to the CBD. The land outside of the centre that was formerly occupied by commercial activities then becomes available for residential purposes which also counteracts suburbanization. Both factors make cities more compact. However, Zakharenko 2016 also remarks that although city size may decrease, average travel distances are not likely to decrease. The reason for this is that the inward 'boundary' of the commuter residential zone (around the CBD) moves inward (see Figure 11) while the outer boundary does not move inwards. In other words, the size of the commuter residential zone increases inwards. The result is that the average travel distances increase (Zakharenko 2016). The travel distances do however not increase as much as in scenario 1 where the city size increases significantly.

Another interesting SAV-driven spatial transformation has been described by Heinrichs 2015. As argued earlier, SAV's can easily be integrated into the conventional public transport network. SAV users also have a financial incentive to make use of conventional public transport. This cross-linkage of different modes of transport leads to the reinforcement and development of mobility hubs (Heinrichs 2015). These 'central transit points' allow for easy transitions between SAV's and other modes of public transport such as train, metro, and lightrail. By developing central transit points, multimodal transport is facilitated and further stimulated which has clear environmental benefits. Heinrichs 2015 also extends the development of transport hubs towards other land uses. He mentions that around the hubs, (new) residential neighbourhoods are likely to be formed. This way, the spatial structure of cities will tend to a polycentric structure based on hubs (Heinrichs 2015), this is displayed in Figure 11. A polycentric city structure has many transport advantages (e.g. fewer congestion) over a monocentric structure (Balcombe et al. 2004). The integrated development of transport hubs is also consistent with the principles of transit-oriented development. Transit-oriented development is a well-known strategy to encourage travel with less energy-intensive modes (Wegener & Fuerst 1999; Balcombe et al. 2004).

The consequences of the usage of SAV's for residential land use are, just like in scenario 1, projected upon the concentric city model by Ernest Burgess. The model in Figure 11 differs from the PAV-scenario model on a number of points. First of all, the CBD is smaller and more concentrated creating room for high density residential development as described earlier. Secondly, public transport has a more dominant role as compared to the PAV-scenario. Especially in the high density zone, public transport has a more important role than road transport. This is partly made possible by the outer transit hubs that facilitate multimodal transport towards and from the CBD. The dominant (S)AV traffic flow is therefore to and from the transit hubs instead of to and from the CBD. Around the transit hubs, new high density residential zones are displayed. Finally, the overall city density is higher (more red) than in the PAV-scenario model. This is because of the higher transport resistance and more intra-urban land supply.

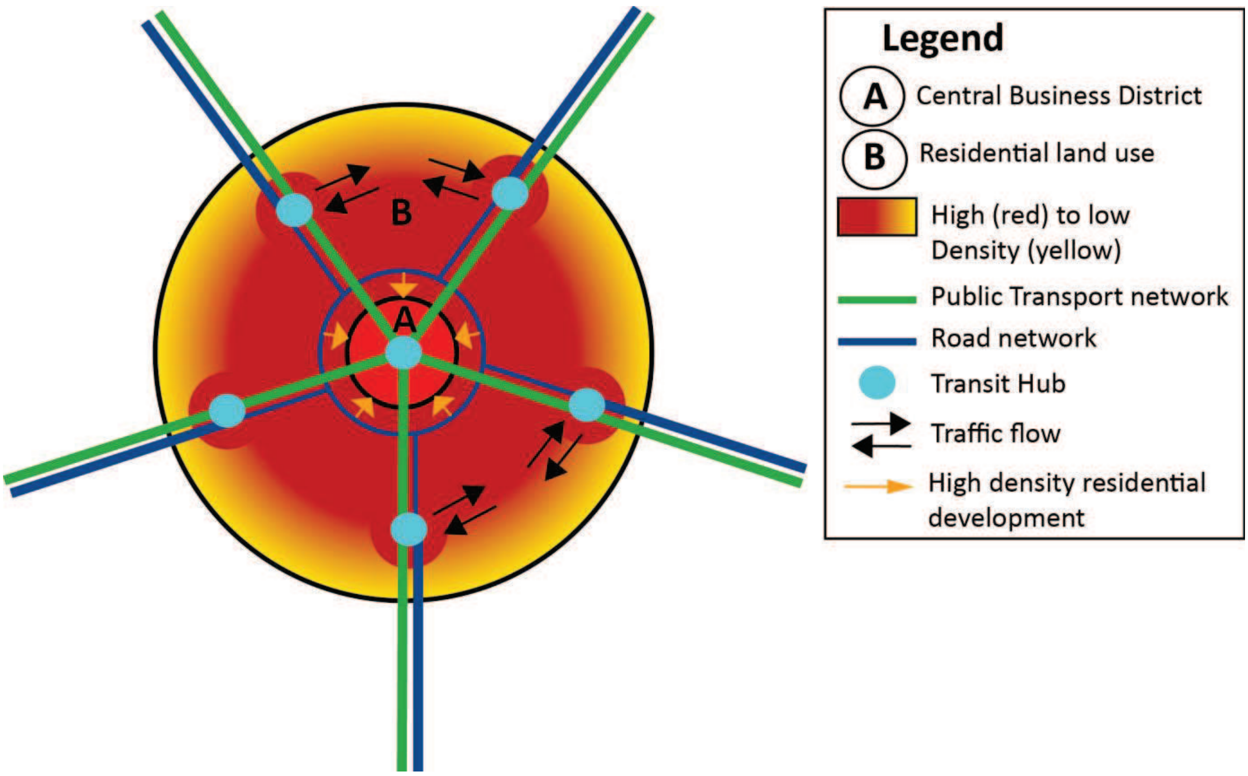

Figure 11: City model illustrating the implications of SAV's for residential land use and transport

Concluding, when compared to PAV's, the usage of SAV's tends to encourage more energy-efficient transport and residential land use.

5.3.3 CAUSAL LOOP DIAGRAM & FEEDBACK LOOPS

The relations between the driving forces that have been described in both the scenario baseline and the SAV scenario above are schematically displayed in Figure 12. Again, the scenario baseline variables that are not affected in this scenario are made a little transparent. The basic layout of this CLD is the same as the previous CLD in scenario 1. The CLD exposes a number of feedback loops that are important in determining the environmental consequences of the use of SAV's.

An important feedback loop involves the empty rebalancing trips that are necessary to rebalance the supply and demand of SAV's. This phenomenon has been described by Gruel & Stanford 2016b and encompasses the following: Car sharing organizations will charge costs of empty vehicle trips and idling vehicles to the users of SAV's. This means that it is in the advantage of SAV users to minimize zero-occupancy rides and the number of idling vehicles. The number of zero-occupancy rides increases whenever there is an imbalance between the supply and demand in an area. For example, during morning rush hour, many SAV's are needed to transport people from "suburbs" to the city where most of the jobs are located. After morning rush hour, many SAV's are therefore located in the city while there continues to be demand in the suburbs. This is when (empty) rebalancing trips are necessary. The greater the imbalance, meaning distance between supply and demand and number of vehicles, the greater the costs. Zero-occupancy rides can also be reduced by adding more SAV's to the car park but this is more expensive. In the end, this implies that suburbanization increases travel costs per kilometre while higher densities with less imbalance decrease travel costs per kilometre (Gruel & Stanford 2016b). In other words, the incentive of scenario 1 to drive further because costs per kilometre will then decrease, has been reversed in this scenario.

Most of the other scenario-specific feedback loops also tend to decrease total energy consumption. Full marginal pricing increases the perceived travel costs which increases transport resistance. In the case of PAV's instead, drivers tend to under-price their trips (Smith 2012). In addition, full marginal pricing increases the attractiveness of multimodal transport. These are trips with more than one mode of transport. Combinations of SAV, public transport, cycling and walking for example. These trips tend to be less energy-intensive. The other feedback loops of the CLD have been explained earlier. The CLD reveals that the overall feedback resulting from SAV mobility is less energy intensive as compared to PAV mobility. Suburbanization and energy consumption are limited by a higher transport resistance and other external factors.

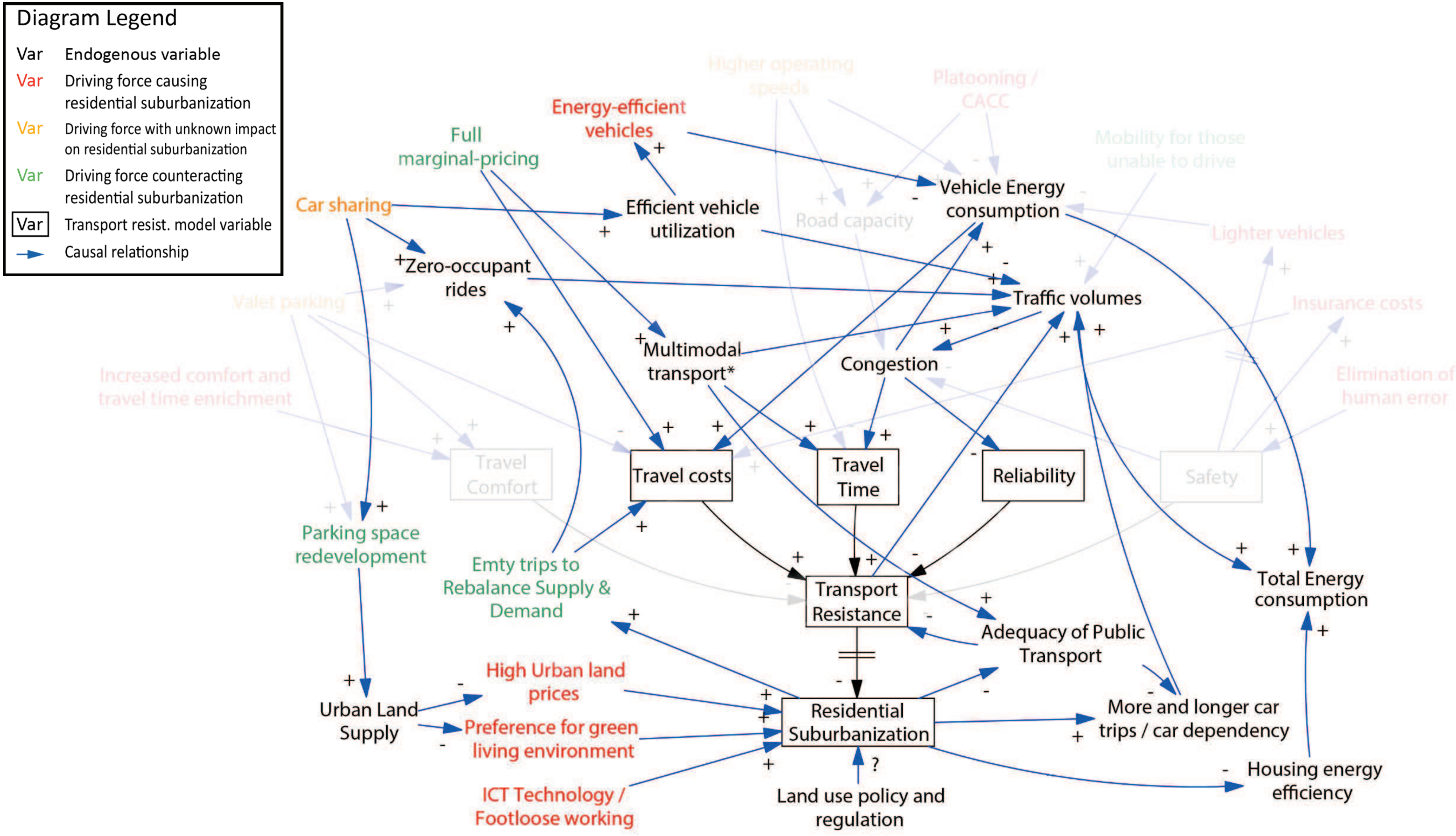

Figure 12: CLD indicating the relation between SAV driving forces, suburbanization and energy consumption (*Multimodal transport = transport via different modes)

6 CONCLUSION

Two scenarios have been described wherein the usage of AV's has become widespread. The scenarios start from the same baseline conditions. These are driving forces with a low degree of uncertainty. In both of the scenarios, travel comfort, travel safety and road capacity have increased and the automobile target market has become larger. However, the scenario-specific driving forces cause a very different outcome for both of the scenarios in terms of residential land use and correspondingly energy-intensity. The AV-related driving forces have an impact on land use because they change transport resistance and (urban) land supply.

In comparison, the scenario that anticipates the dominance of SAV's results in less energy-intensive residential land use than the scenario that anticipates the dominance of PAV's. The SAV scenario is less energy-intensive in terms of both land use and transport. The reason for this is that the SAV scenario incorporates a number of driving forces and feedback loops that increase transport resistance and counteract suburbanization drivers. The PAV scenario on the other hand lacks sufficient feedback loops and driving forces to counteract the decrease in transport resistance that emerges from the baseline driving forces. The major causes for the different outcomes of both of the scenarios will be described below.

First of all, a major difference between the usage of PAV's and SAV's is the pricing mechanism. SAV's can overcome the opaque pricing of privately-owned vehicles and thereby SAV's reduce the incentive to drive excessively. Secondly, SAV's can be more easily integrated with public transport networks and SAV users are economically stimulated to use public transport. Thirdly, less vehicle ownership and more efficient vehicle utilization due to car sharing decreases the number of cars that have to be built and parked. This is, to a greater extent, true for the SAV scenario. Less vehicle ownership in itself decreases energy consumption. Additionally, a reduced need for parking in combination with more efficient parking significantly reduces the need for parking space. This allows for higher residential densities which are more energy efficient in terms of transport and housing energy efficiency. Fourthly, car sharing also allows for a better matching of trip purpose with vehicle type. For a majority of the trips, lighter and more energy-efficient vehicles can be used while heavier vehicles remain available to the user. Finally, the trip price of SAV's depends on the geographical balance in the supply and demand of trips. Denser (residential) land use patterns result in lower SAV trip prices. SAV's thereby encourage more dense and sustainable land use patterns.

When the driving forces and feedback loops of both of the scenarios are projected upon a concentric city model, two different patterns emerge. The PAV scenario city model shows a classic increase in city size that is the result of more low density residential developments at the edge of the city. This increase in city size is enabled by a lower transport resistance and subject to land use policy and regulation. The PAV scenario city model reveals a more complicated spatial development in which overall density increases. Besides, the spatial structure of the transport system shifts towards a more polycentric structure that also supports high density transit-oriented residential developments. As argued, high density residential developments are more favourable in terms of energy-usage and sustainability. This leads to the following conclusion: The impact of the widespread usage of SAV's is less energy-intensive in terms of both residential land use and the corresponding transport interactions as compared to the impact of the usage of PAV's.

7 DISCUSSION

As the title already mentions, this is an explorative study. The reason for this is that large scale AV-dominated mobility systems do not yet exist. That means that all of the presented quantitative data about AV's is based on model studies, scenario studies and expert input. In other words, this data is based on certain assumptions. However, when possible, a range of outcomes has been provided to account for the level of uncertainty. On top of that, many studies have been combined to ensure triangulation of the data. Fact remains that the data is not to be regarded as rigid and definite.

The system dynamics approach has been used to systematically link many cause and effect relations to each other. A fundamental step of this approach is the definition of a system boundary. It is impossible to incorporate the indefinite number of feedback loops involved in land use and transport interactions. The focus has been on the major AV-related forces that have an impact on residential suburbanization and other direct system-wide driving forces of residential suburbanization. That doesn't mean that there are no other factors that influence the presented system. However, *"it means that what crosses the boundary is not essential in creating the causes and symptoms of the particular behaviour being explored"* (Forrester 2017, p.406).

Two scenarios were plotted using the intuitive logics method. As Xiang & Clarke 2003 argue, a range of two to seven scenarios is considered generally acceptable. This implies that two scenarios is the absolute minimum. The number of two was chosen because of the limited timeframe of this Thesis research. The limitation of the usage of a minimum number of scenarios is that when you pick the wrong differentiating variable, the scenarios may not be relevant (Townsend 2014). To overcome this pitfall, chapter 4 has been specifically dedicated to the selection of a solid differentiating driving force. Many driving forces have been considered and evaluated in this chapter.

This research has been a first step towards the development of a spatial policy analysis framework that ensures the sustainable implementation of AV's. A possible next step is to further model and quantify the cause and effect relations incorporated into the CLD's. The development of CLD's is after all, only the first, yet essential step in the elaborate system dynamics approach (Haraldsson 2000). Another important aspect to be researched is the impact AV's have on other land uses such as commercial, recreational and industrial uses. Only when the impact of AV's on these land uses has been explored, it is possible to fully estimate the impact AV's have on total energy consumption and land use.

8 RECOMMENDATIONS

In response to the conclusion formulated above, it is recommended to discourage the usage of privately-owned autonomous vehicles in favour of the use of shared autonomous vehicles. SAV's are able to fulfil the mobility needs of a large part of society while being more energy-efficient. SAV's also tend to stimulate more sustainable land use and travel behaviour. The need to stimulate SAV popularity and usage is reinforced by recent studies into AV user preferences. Piao et al. 2016 did a survey study and found that of the potential AV users, only 27% indicated that he/she would use SAV's instead of PAV's. This percentage is even lower for the respondents with lower education. In another survey study, Haboucha et al. 2017 found that costs are an important variable in consumer choices regarding shared versus privately-owned AV's. However, they also found that 25% of the individuals would refuse to use SAV's even if their usage is completely free. People who never use public transport today, are also less likely to use SAV's in the future (Haboucha et al. 2017). Environmental concern was found to be an important factor for people to prefer SAV's over PAV's.

Haboucha et al. 2017 suggests that educational campaigns are important in changing people's attitudes towards the usage of AV's and SAV's. Other policy instruments to stimulate SAV usage over PAV usage can be derived from the transport resistance model. By influencing the travel comfort, travel costs, travel time, reliability and/or safety of PAV's or SAV's, travel behaviour can be altered. However, safety is obviously not to be compromised. A widely applied policy instrument in transportation planning is financial manipulation. For example, when the usage of PAV's is made more expensive through road use charges or tiered road-pricing as suggested by Gruel & Stanford 2016b, SAV's become more attractive. As family PAV sharing requires more zero-occupant rides than SAV usage, the prohibition of these rides would also stimulate the usage of SAV's (Gruel & Stanford 2016a). Another option is to only allow AV rides to and from transit hubs. For these rides, SAV's are more suitable as they require no parking and can reduce costs by ride sharing. With financial manipulation, the overall AV usage can optionally also be reduced. Other policy instruments to reduce overall AV usage are: a reduction of operating speed by setting speed limits, limiting travel comfort by requiring an attentive driver at all times and the stimulation of public transport usage (Gruel & Stanford 2016b).

The final policy instrument that can be used to encourage SAV usage and energy-efficient land use is, as mentioned in all of the CLD's, Land use policy and regulation. By restricting residential suburbanization and facilitating dense development, many of the negative effects of the usage of AV's can be mitigated. However, land use regulation in this context is only a way of fighting the symptoms of AV usage. Therefore, it is better to combine land use regulation with one or more of the policy instruments mentioned above.

In the light of the far-reaching consequences AV's can have on travel behaviour and land use, the worst thing to do would be to do nothing and only highlight possible advantages that AV's bring. This is exactly what the Dutch government currently seems to do. Although AV's can solve a lot of the current mobility problems, they can also cause new problems. In this study, favourable and unfavourable, direct and indirect implications of AV usage have been addressed in the hope that this will lead to a more refined future mobility and land use system.