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The deployment of automated vehicles in urban transport systems: a methodology to design dedicated zones

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Abstract

Vehicle automation is not yet a reality which casts huge speculation of what will really happen when implemented in the near future. The effective deployment of such novelty, especially full automation, foresees potential impacts at different levels, the most direct ones being on the mobility level. Since the deployment of fully automated vehicles cannot be realized instantaneously in all areas of a city, a transitional phase must be assumed to mitigate the changes to come. It is critical to devise policies in order to implement such technology to leverage the benefits that it may bring. According to a literature review, deployment on urban networks revealed to be a gap in the literature. In order to address that gap, we want to support city planners by developing a strategy of integration for such technology into urban networks. At a traffic level, a strategy of dedicated zones for automated vehicles will be settled. We develop a model whereby the aim is to minimize the congestion problem through dedicated links where only automated vehicles can drive. A traffic assignment approach is used where the minimization of the sum of link travel times is part of the objective function. The number of automated vehicles is changed in function of a penetration rate. Each scenario is simulated and compared. This study begins the discussion of how to help public authorities plan the deployment of such automated vehicles and bring improvement to traffic in cities.

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Keywords: automated vehicles; transport planning; traffic; optimization; simulation

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1. Introduction

Over the last century, transportation systems evolved due to social and economic pressure alongside technology development. The performance of these systems creates impacts at several levels and influences accessibility and mobility of cities. The enhancement of mobility sustainability, a concern that was raised in the meantime, is occurring gradually and is mainly fostered by urban planning strategies, new technologies and the improvement of public transport within cities. In the past two decades, an increased interest has been growing towards vehicle automation which brings great potential changes on mobility in urban centres. In fact, the advancements in vehicle automation might enhance the current mobility system but there are concerns that it might disrupt the current transportation paradigm in a way that is still difficult to foresee.

In urban environments, automated vehicles (AVs) are believed to begin as speedy last mile taxis by 2020 whereas automated taxis will only become a reality by 2028. The deployment of AVs in urban environments is expected to start with segregated lanes and then with dedicated lanes by 2020 and mixed with conventional vehicles (CVs) by 2028 (Zlocki 2014).

The research done so far involving these topics is nearly inexistent. The following study is an initial experiment of a research focused on the AV deployment in urban centres. Therefore, this initial paper is focused on the design of dedicated links that will help to form zones/cordon areas for automated vehicles-only policy. We believe that such strategy is promising to achieve more effectively the benefits that AVs might bring, especially assuming the existence of V2I (vehicle-to-infrastructure) communication where is possible to control AV traffic.

This paper is majorly focused on traffic improvements, i.e. to minimize the sum of link travel times of the network in a "system approach". The following model comprises a benefit analysis which compares a previous scenario where AVs don't exist with a futuristic scenario where AVs circulate in their dedicated zones more efficiently but also in the rest of the network mixed with CVs. The model computes the amount of travel time saved between the preceding scenario and a scenario with dedicated roadways for AVs. Additionally, a walking penalty occurs to parts of the network where CV cannot travel. Also, an infrastructure cost for V2I communication is considered to each AV dedicated link.

The paper is organized as follows. Section 2 presents the literature review. Section 3 proposes a mathematical model to select dedicated links. Section 4 documents the numerical experiments in a small network. Finally, Section 5 draws the conclusions and future work.

2. Literature review

The literature regarding automated vehicles is scarce and disperse. Most of the significant existent research covers the vehicle technical features and the forthcoming impacts in interurban traffic environments, mainly focused on traffic capacity (Correia et al., 2015).

The few studies specifically related with deployment staging of AVs are intended to interurban highways. In 1997, van Arem and Tsao stated two approaches of deployment: the geographical approach where it is implemented in one step and expand geographically; and the functional approach, that considers that the deployment cannot be realized suddenly once considerable difficulties may be encountered in reality. Also in 2000, Shladover stated different paths for functional deployment, noticing that it can occur differently over regions: ones with connectivity and adaptive cruise control and, in other regions, with only dedicated lanes. Our paper follows the functional approach where a transitional stage and intermediates steps (e.g. penetration rate) must be identified and optimized to best adapt the technology towards reality.

Research studies are scarce in urban areas where such deployment is expected to have significant impacts that are difficult to determine because of the uncertainty about AV and its interaction with pedestrians, cyclists and CV. Milakis et al. (2017) listed the impacts that AV deployment might bring and divided in three ripples that are interdependent with each other. This "ripple effect" model portraits the effects that AVs might bring in mobility, urban form and societal implications, respectively. Our paper is majorly focused on the improvement of traffic (mobility ripple) to calculate the optimal scenario that achieves more societal benefits.

Regarding the mobility and AV deployment, literature is growing but still highly limited. Correia and van Arem (2016) recently published a study that assesses the impacts on traffic delays and parking demand if private CVs were replaced by AVs. Their model minimized the total transport costs of all families in the city (system optimal approach) and afterwards minimized each individual household transport costs. The results revealed that traffic congestion increases up to 5.04% when the existence of empty vehicles is significant. The percentage of empty kilometres along the scenarios ranged between 10.3% and 87.4% of which the last regards a scenario where there is paid parking everywhere. In scenarios with lower value of travel time (VTT) the car mode share increased and congestion was reduced. Overall, AVs reduced generalized transport costs and satisfied more trips demand.

Therefore, the effect of AV deployment is uncertain. The strategy of restricting some parts of the urban networks seems an interesting point of view for AV deployment. A system-optimal scenario can be put in practice if these zones with V2I connectivity allow the control of traffic. Nowadays, the restriction of part of the network is not novel in transportation paradigm. It might happen either to reduce pollution reasons or to restrict to pedestrians/bikes/bus.

Recently, Chen et al. (2017) have published a framework for the optimal design of AV zones in a general transportation network. Their bi-level problem is solved sequentially, where the lower-level problem is the “mixed routing equilibrium model” to capture mixed-routing behaviours between AVs and CVs, solved linearly; and the upper-level problem regards the optimization of the deployment plan to select the AV zone, solved by a simulated annealing algorithm.

Our paper presents an initial study to solve the problem of selecting AV dedicated zones by mathematical programming which forces some generalisations. The typical non-linearity of this problem is the major drawback that might set the following model to a road network design problem which is a useful tool to properly plan networks, given a known demand, supply and constraints of the problem. The traffic assignment (TA) methods and travel time functions are the two major aspects that influence our model.

The popular method to do the traffic assignment of car flows to a road network is the Wardrop (1952) principle which considers capacity constraints and may also consider stochastic effects. Theoretically, there are two approaches: the user-equilibrium and the so-called social equilibrium. In the user-equilibrium approach, each individual trip maker has a selfish behaviour and aims at decreasing his own travel time to a point that there are no better alternatives. In the social equilibrium approach, the solution is the one that minimizes the travel time of all road users which might be realistic if AVs are connected with the infrastructure. However, the proposed model engages a static traffic assignment (non-time-dependent), solved to optimize the system through the minimization of the average travel times in all links of the network. Therefore, it is not a social-optimal equilibrium because there is not a minimization of the travel times for all the users in the network.

Concerning the travel time functions, the most accurate are the polynomial, exponential, and even time dependent (Akcelik, 1991). However, a linear travel time function is used in this initial study.

3. Methodology to design dedicated zones

We present a method to select dedicated zones whose main objective function is the improvement of the traffic performance as this formulation is simpler to define in a static mathematical programming. As said before, our problem fits into a discrete road network design problem where a system perspective is taken into consideration for the distribution of the traffic flows. The assumptions of our model are:

- The trips performed are either done by AVs or CVs, according to their penetration rate which is an input;
- Each trip is assigned to one car (a person by car);
- An AV is considered to be level 4 (SAE, 2014) which means that inside dedicated areas they drive automatically;
- In a trip done in a CV, when the car reaches the boarders of the dedicated area, it is considered that the traveller will walk toward the final destination;
- AVs travel more efficiently than CVs, allowing an increase of capacity of the roadway;
- No external trips to the city are considered in the network.

The model is formulated as a discrete integer programming problem, as follows:

Sets:

I	(1, …, i, …, I) set of notes in the network, where I is the number of nodes.
R	$\{\ldots,(i,j),\ldots\}\ i,j\ \in I, i\neq j$, set of arcs of the road network where vehicles move.

Data:

D_{ij}	trips from node i to node j, $\forall\ i,j\ \in I$.
D_{ij}^{AV}	trips of automated vehicles from node i to node j, $\forall\ i,j\ \in I$.
D_{ij}^{CV}	trips of conventional vehicles from node i to node j, $\forall\ i,j\ \in I$.
t_{ij}^{min}	minimum travel time in road link (i,j), $\forall\ i,j\ \in I$.
t_{ij}^{max}	maximum travel time in road link (i,j), $\forall\ i,j\ \in I$.
L_{ij}	length of each link (i, j) in kilometres $\forall\ (i,j)\ \in R$.
Q_{ij}	capacity of each link (i, j) in vehicles per time period $\forall\ (i,j)\ \in R$.

Parameters:

α	traffic efficiency coefficient that reflects the benefit that AVs have on capacity, i.e. the number of CV to which an AV corresponds to (between 0 and 1).
ρ	percentage of AVs on the fleet (between 0 and 1).
τ	travel time in minutes per kilometre of walking inside dedicated zones.
μ	parameter that reflects the "walking capacity" of the network
VTT	value of travel time in monetary units per hour.
$Cost_{V2I}$	cost of implementation V2I communication per dedicated link for AVs.
$TT_{\rho=0}$	Sum of link travel times with a null penetration rate (only CVs)
M	Big value

Decision variables:

x_{ij}	binary variable equal to 1 if road link (i, j) is assigned for AVs only driving, $\forall\ (i,j)\in R$.
f_{ij}^{AV}	integer variable that corresponds to the AV flow in each arc (i, j) $\in R$.
f_{ij}^{CV}	discrete variable that corresponds to the AV flow in each arc (i, j) $\in R$.
w_{ij}	discrete variable that indicates the flow of CV trips that are not allowed in AV zones and therefore require walking in each link (i, j) $\in R$.
t_{ij}	car travel time in link $(i,j)\in R$
$t^{w}{}_{ij}$	walking time in link $(i,j)\in R$.

Some societal effects accrue from the implementation of dedicated zones. In this model, we considered the benefit of introducing AVs and dedicated links when compared with the current scenario (no AV deployment). Plus, a walking penalty is considered for the trips done with CVs that are not allowed to circulate inside AV zones. Trips must reach their destination and the model must consider that part of those trips are done walking. Finally, the model considers a cost to implement V2I communication in these AV dedicated links. Therefore, this analysis aims to maximize the benefits, expressed in monetary units, as expression (1) details.

$$\text{Max(Benefits)}=(TT_{\rho=0}-\textstyle\sum_{i,j\in I}\ t_{ij})*VTT-\sum_{i,j\in I}\ tw_{ij}*VTT-\sum_{i,j\in I}\ x_{ij}*Cost_{V2I} \quad (1)$$

The objective function is subject to the constraints expressed between (2) and (22).

$$\textstyle\sum_{j\in I}\ f_{ij}^{AV}=\sum_{j\in I} D_{ij}^{AV}\ ,\forall i\in I \quad (2)$$

$$\sum_{i\in I} f_{ij}^{CV}=\sum_{i\in I} D_{ij}^{CV} \ ,\forall i \in I \quad (3)$$

$$\sum_{i\in I} f_{ij}^{AV}=\sum_{i\in I} D_{ij}^{AV} \ ,\forall j \in I \quad (4)$$

$$\sum_{i\in I} f_{ij}^{CV}=\sum_{i\in I} D_{ij}^{CV} \ ,\forall j \in I \quad (5)$$

$$\sum_{i\in I} f_{ij}^{AV} - \sum_{i\in I} f_{ji}^{AV}=0 \ ,\forall j \in I \quad (6)$$

$$\sum_{i\in I} f_{ij}^{CV} - \sum_{i\in I} f_{ji}^{CV}=0 \ ,\forall j \in I \quad (7)$$

$$f_{ij}^{AV} * \alpha + f_{ij}^{CV} \le Q_{ij} + x_{ij} * M \ ,\forall (i,j) \in R \quad (8)$$

$$f_{ij}^{AV} * \alpha \le Q_{ij} + (1 - x_{ij}) * M \ ,\forall (i,j) \in R \quad (9)$$

$$f_{ij}^{CV} \le Q_{ij}(1-\rho) \ ,\forall i,j \in I \quad (10)$$

$$f_{ij}^{AV} \le Q_{ij} * \rho \ ,\forall i,j \in I \quad (11)$$

$$w_{ij} \ge f_{ij}^{CV} - (1 - x_{ij}) * M \ ,\forall i,j \in I \quad (12)$$

$$w_{ij} \le f_{ij}^{CV}, \forall i,j \in I \quad (13)$$

$$w_{ij} \le Q_{ij} * x_{ij}, \forall i,j \in I \quad (14)$$

$$x_{ij} \le f_{ij}^{AV}, \forall i,j \in I \quad (15)$$

$$x_{ij} \le f_{ij}^{CV}, \forall i,j \in I \quad (16)$$

$$t_{ij}= t_{ij}^{min} + \frac{f_{ij}^{AV} * \alpha + f_{ij}^{CV} - w_{ij}}{Q} * (t_{ij}^{max} - t_{ij}^{min}) \quad (17)$$

$$tw_{ij}= \frac{w_{ij}}{..} * \tau * L_{ij} \quad (18)$$

$$x_{ij} \in \{1,0\} \ ,\forall (i,j) \in R \quad (19)$$

$$f_{ij}^{AV}, f_{ij}^{CV}, w_{ij} \in N^0 \ ,\forall (i,j) \in R \quad (20)$$

$$t_{ij} \in R \ ,\forall (i,j) \in R \quad (21)$$

$$tw_{ij} \in R \ ,\forall (i,j) \in R \quad (22)$$

Constraints (2) and (3) assure that trips are generated in the centroid nodes where trips start for AVs and CVs, respectively. Constraints (4) and (5) assure that trips are absorbed in the destination nodes for AVs and CVs, respectively. Constraints (6) and (7) assure the equilibrium in the nodes, i.e. the balance between the flow that arrives and departs must be null for AVs and CVs, respectively. Constraints (8) and (9) assure the capacity limitation in each link in the network. Whereas expression (8) constraints the mixed flow in links that are not exclusive for AVs, expression (9) assures that in dedicated links AVs flow is up to the capacity of that link. Constraint (10) assures that there is no CVs flow when the AV penetration rate is equal to 1. Constraint (11) assures that there is no AVs flow when the penetration rate is null. From constraint (12) to (14), the existence of a walking flow is assured in dedicated links where CVs flow exists. Whereas expression (12) details that walking flow must be higher than CVs flow in dedicated zones, constraint (13) forces to take that exact value as the conventional flow. Constraint (14) assures that walking flow is true in AVs links, beyond those places walking flow is null. Constraint (15) details that AV dedicated links are necessary in places where AVs flow circulates. Constraint (16) assures that, when full deployment (i.e. CV flow is null), there is no decision for AV links because the problem no longer exists.

Equations (17) and (18) calculate the link travel times by car and walking, respectively. Constraints (19) to (22) set the domain of the decision variables.

4. Numerical experiments in a small network

We applied the model to a grid symmetrical network, composed of 49 nodes and 84 arcs with two ways of circulation. The trips were equally distributed in eight nodes (1,4,7,22,28,43,46,49) with the sole destination in the central node (25). In order to give some realism to the network, speed and capacity decrease towards the centre of the network. Since the central node is surrounded by just 4 links, the maximum number of trips was limited to the sum of those capacities for the traffic assignment period being considered

Another important aspect of the model is the travel time function which is linear. The minimum travel time in each link is calculated in free flow speed whereas the maximum travel time in each link occurs when capacity is reached and speed turns 10% of the free flow speed. Regarding the efficiency coefficient (α) that details the effect of AVs on traffic, it was considered that AVs benefit capacity of 25% all over the network. Calvert et al. (2011) found a benefit around 22 when penetration rate is 50%. The value of travel time was considered 10 monetary units per hour. The walking time considered a pedestrian speed of around 4 km/h. Note that walking capacity (μ) is needed to compare at the same units both car travel and walking time, which was considered 4000 persons. The cost for V2I infrastructure in each link was considered 300 monetary units.

The model was implemented in the Mosel language and solved using Xpress 7.7, an optimization tool that uses branch-and-bound for solving MIP problems (FICO, 2014). Each scenario was run in a computer with a processor of 2.9 GHz Intel Core i5 and 8GB RAM.

4.1. Implications on traffic

In a first experiment, we ran the model by minimizing the link travel times in the network, only considering car traffic, as expression (23) details.

$$\text{Min}(\text{sum of link travel times}) = \sum_{i,j \in I} t_{i,j} \tag{23}$$

Table 1. The effect of the penetration rate on the sum of link travel times

Penetration Rate	Sum of link travel times (min)	No. of dedicated links for AVs
0.00	208.83	0
0.10	116.07	15
0.25	128.16	15
0.50	148.33	16
0.75	168.50	17
0.90	180.60	19
1.00	188.67	0*

* In this scenario, all network is already for AVs only.

Table 1 presents the results for different penetration rates. Congestion happens when there are no AVs in the network. Two patterns on the results from Table 1 can be distinguished. The first regards the scenario where the AVs percentage is 10% where the existence of dedicated links reduce significantly the travel times. Subsequently, that value slightly increase as more AVs enter in the network and the travel times inside dedicated zones slightly rise. The second pattern shows that when the penetration rate becomes significant, the need for AV dedicated links is obvious. It is also noticeable that the number of links for AV rises alongside with the penetration rate.

4.2. Model results: societal benefits analysis

The model defined by the objective function (1) maximizes the benefits by selecting dedicated zones for AVs. Several scenarios were created varying the ratio of the number of AVs and CVs and Table 2 presents the results.

Table 2. The effect of penetration rate on the societal benefits.

Penetration Rate	Benefit cost (monetary units)	No. of dedicated links for AV
0.00	6,666.67	0
0.10	2,498,227.70	14
0.25	2,216,831.15	14
0.50	1,747,602.67	14
0.75	1,278,407.32	14
0.90	996,800.00	14
1.00	813,333.33	0*

* In this scenario, all network is already for AVs only.

Similar to what happened in traffic analysis, the scenario with the highest benefits were achieved in the beginning of the AV deployment. Therefore, the pattern of travel times shown in the previous model are also present here. However, the number of links selected for AVs was lower in comparison with the previous experiment. Moreover, it seems that the penetration rate does not have effect on the number of links selected for AVs like in the previous experiment. Both situations were expected to happen since other costs, such as walking time and V2I communication, are part of the objective function. Figure 1 presents the network for a scenario when ρ=0.75.

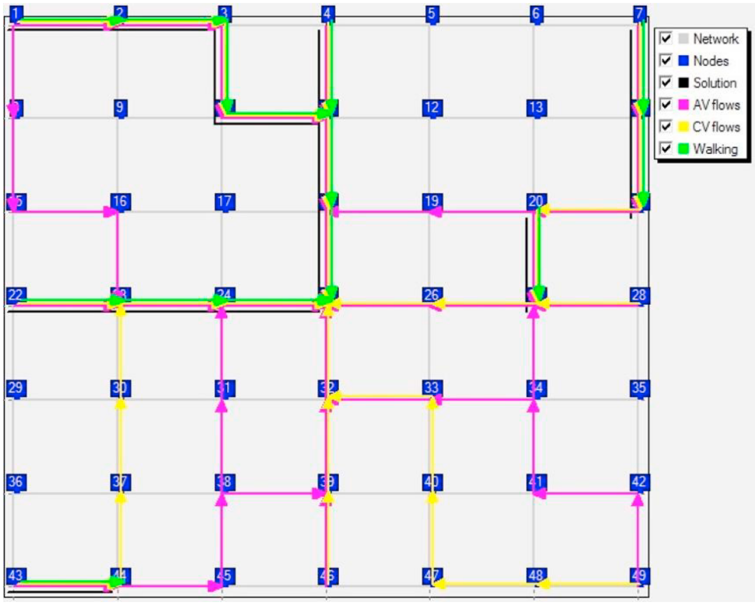

Fig. 1. Optimal solution for the scenario with a high AV penetration rate ($\rho = 0.75$).

5. Conclusions and future work

This paper presents a first study to design dedicated zones for AVs. Our model considered some implications that AV technology might bring in the future, like V2I communication and the penalty that CVs will experience when not allowed to travel in some parts of the network.

Since our mathematical model is linear, some generalizations were performed. The main drawback of this model remains in the static traffic assignment, which is a limitation in terms of the realism of the results. Congestion cannot be perceived because trips always reach their destination without queues in the network (not time-dependent). Also, the travel time function is linear which does not happen in reality. The model does not guarantee the path of the vehicles but rather the direction of the flow, i.e. the model is not aware of the length of the trips. Another generalization regards the global effect of the penetration rate on the whole network rather than by origin-destination trip. Additionally, the traffic efficiency coefficient, i.e. the benefit of AVs to capacity, is constant whether the AV is inside or outside cordon areas. Moreover, it should also take into account as its parameters the penetration rate and the type of road (cordon areas or not). Furthermore, walking time is in function of a walking capacity coefficient to compare at the same units both car and walking travel times. Therefore, these are the major points to improve in future works towards a dynamic traffic assignment with detailed congestion metrics that help decide which zones of the network should be dedicated for AVs.

Despite the limitations of the model, it is noticeable that dedicated links might be an option for future policy because it helps reduce the travel times all over the network. Since the model is static, the computed AV links appeared arbitrarily in the network. However, dedicated zones near the centre of the network would be expectable to happen.

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