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Service Network Design for Same Day Delivery with Mixed Autonomous Fleets

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Abstract

Two-tier city logistics is a well-established concept to achieve high levels of consolidation in urban freight distribution. With the recent shift towards offering same day delivery, service providers in parcel delivery are looking at new solutions to deal with the resulting challenges. We introduce autonomous vehicles as an upcoming technology to this field of research and consider a mixed fleet in the first tier of city logistics. Because autonomy cannot be ensured on all roads of the network, we handle the heterogeneous infrastructure with manually operated vehicles serving as platoon leaders. In our proposed MILP formulation of service network design for autonomous vehicles in platoons (SNDAVP), we show how platooning can be incorporated into this tactical planning problem. Computational experiments on first instances are conducted using CPLEX.

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Keywords: service network design; city logistics; autonomous vehicles; platooning

1. Introduction

Service providers in parcel delivery are facing a variety of operational challenges when offering same day delivery to their customers. Due to incoming requests on the go and continuously arriving supply, delivery vehicles return to loading facilities more frequently over the day.

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Operational costs rise quickly if service providers answer small-volume requests with an excessive number of stops per delivery route. Achieving a high level of consolidation in operations is crucial for a cost-driven industry like logistics. This is particularly challenging in cities, where a large share of demand in parcel delivery originates from. Especially in dense urban areas, space for transshipment between vehicles is scarce. City logistics models are used to optimize operations of service providers. Two-tier city logistics in particular aims to establish consolidated transports in the first tier of urban freight distribution, which covers the transportation from external zones on the periphery to satellites inside city centers (Crainic, 2008).

Autonomous vehicles (AVs) are expected to substitute a significant share of personal mobility and public transit from the next decade onwards. For delivery applications, however, they are yet to be conceptualized. After surveying current research advances, we decide to consider vehicles with conditional automation. In this level of automation, the vehicle is able to perform all driving tasks by itself in specific conditions only. In difficult conditions, a human driver has to serve as a fallback to the system. This paper aims to integrate mixed autonomous fleets into the first tier of city logistics. The main complexity of the emerging service network design problem lies in the synchronization of the heterogeneous fleet to fulfill demand in a cost-efficient way. However, AVs are not equivalent to conventional delivery vehicles with a human driver as long as they are not able to travel on all areas of the network. In conditional automation, only some zones are feasible for AVs to move on without a driver. Such AV zones can be characterized by having dedicated lanes, easy-to-handle junctions, certain speed limits or specific traffic rules.

One possible solution to bridge the gaps between AV zones in the network is platooning. A platoon describes a group of multiple vehicles following each other closely. A manually operated vehicle (MV) can serve as a leader and takes over the navigation task for the AVs behind. Thereby, the human driver in the MV fulfills the necessary fallback function for the following AVs with conditional automation. Platoons permit to use less road space in contrast to moving separately and achieve a total transportation capacity similar to much larger vehicles. Despite having the mentioned option of consolidation, flexibility in route choice is retained by moving as individual vehicles. Platooning can be viewed as a technology to utilize the benefits of conditional automation until fully automated technology is ready to market. In accordance to that, our proposed model considers platooning to transfer autonomous vehicles through parts of the network, in which the automated driving system is unable to operate. It is also advantageous that the following vehicles of a platoon do not need to have a human driver because the MV in front acts as a fallback. This leads to different itineraries compared to a conventional, homogeneous fleet. To integrate this approach into a tactical planning model for city logistics, we introduce service network design for autonomous vehicles in platoons (SNDAVP).

The remainder of this paper is organized as follows. In Section 2, we review known concepts in two-tier city logistics as well as current research advances for autonomous vehicles and their future applications in logistics. Section 3 starts with a description of the problem we apply our service network design model to. After a detailed explanation of the underlying time-expanded network for the model and its mathematical formulation, Section 4 contains results of the conducted computational experiments. Finally, Section 5 concludes with perspectives on further steps regarding the stated problem.

2. Related research

Since we are not aware of any literature specifically addressing mixed autonomous fleets in a city logistics planning problem, we describe the two key foundations for our contribution in this section. First, the concept of two-tier city logistics is explained as the area of application for the model. Further, we outline recent research advances in automated driving and state the basic principles of platooning. These technologies serve as a motivation for the SNDAVP.

2.1. Two-tier city logistics

City logistics pursues effective and efficient transportation of goods in urban areas. While service providers in transportation typically aim to minimize individual costs, city logistics further recognizes the impact of their operations on traffic and the environment (Savelsbergh and Woensel, 2016).

Since urban population continues to grow and cities become more crowded, the challenge to consider those negative effects and still provide a profitable service becomes even more difficult. Furthermore, e-commerce growth and the trend towards offering same day delivery continuously lead to an amplification. This issue keeps researchers busy to this day, having led to a variety of different frameworks to optimize city logistics services. A common objective in most of these model applications is the reduction of freight vehicles in the city and their distance traveled.

According to Crainic (2008), consolidation and coordination are the fundamentals for successful city logistics planning. Consolidation can be achieved if various shipments are pooled and assigned to a single vehicle. Coordination is enhanced by considering the fleets of multiple service providers. One commonly used approach to incorporate both of these aspects introduces city distribution centers (CDCs) on the city's periphery. Incoming loads from long-haul transportation are unloaded, sorted, and consolidated into smaller vehicles that deliver them to urban destinations. Inbound flow of goods represents the largest share of load volume in most cities. This is why the majority of city logistics literature focuses on inbound flow only. Nevertheless, outbound flow and shipments within the city can be considered to further improve consolidation in cities (Crainic et al., 2012).

Two-tier city logistics describes an advancement of the single-tier case. Satellites are introduced as transshipment terminals, dividing freight distribution into a first and second tier. They permit for vehicles to park in order to transfer goods between each other. Since mere parking lots or bus garages are utilized, storage of goods is not provided. In a conventional inbound system, goods appear in external zones outside the city center, where nearby highways or (air)ports enable the arrival of high-volume shipments. CDCs as part of external zones act as consolidation hubs for multiple service providers and pool incoming goods. Urban trucks are used for the transport to inner-city satellites in the first tier. Their routes preferably take place in dedicated corridors like "ring highways", taking traffic and emissions into consideration. In the second tier, city freighters usually cover the last mile delivery between satellites and customers. These vehicles with smaller load capacities are able to travel on any given street in the city, emitting less noise and gas than trucks.

The implementation of vehicle routes to minimize costs of the service provider is regarded as the day-before planning problem (Crainic et al., 2009). The tactical aspect of this problem concerns urban-vehicle service network design (UVSND), where itineraries from external zones to satellites are determined in a time-expanded network. We focus on this first tier to specifically address the restocking of satellites and synchronization of the fleet. City-freighter circulation models further assign deliveries from satellites to end customers from an operational perspective. An alternative to this detailed decomposition approach is proposed by two-echelon vehicle routing formulations (Perboli et al., 2011). Recent notable contributions to the research area include multi-modal transportation (Fontaine et al., 2017) and the vision to progress towards hyperconnected city logistics (Crainic and Montreuil, 2016).

2.2. Autonomous vehicles and platooning

In this section, we briefly review the current state of research in automated driving. Then, we introduce applications in transportation, which heavily rely on platooning at this point. The 6 levels of driving automation are defined in standard J3016 by SAE International (2016). Level 0 provides no automation, while levels 1 and 2 assist the driver partially. While such systems greatly contribute to traffic safety and convenience for the driver, their economic impact on industrial applications is negligible as long as driving staff is still needed. From level 3 upwards, an automated driving system monitors the driving environment, thus performing the entire dynamic driving task. In conditional automation (level 3), the human driver still serves as a fallback to take back control from the system. In addition, the automated driving system is only capable of some driving modes like highway cruising, low speed traffic jams or operations in closed areas. In level 4 (high automation), the fallback is provided by the system. Level 5 ensures full automation in all driving modes. While this classification delivers technical guidance, the legal foundation for driverless vehicles is still vague. Vehicles with automation level 3 to 4 seem plausible to appear in the next few years, which is why we focus on them in our research.

At this point, the effects of automated driving in logistics are hard to predict. Therefore, industry and academia consider several scenarios and use cases. Some of them are inspired by warehousing and outdoor logistics operations, where fully automated systems already contribute to increased efficiency.

In last mile delivery, DHL imagines self-driving parcel stations (Heutger, 2014), while start-ups like Starship (www.starship.xyz) deploy small robots on sidewalks. For transportation on open street networks, fully automated solutions are still out of sight for the next years. Platooning or convoying is seen as an opportunity to utilize automated driving capabilities if conditions enable it. When the driver of the first vehicle takes over the lead function for a platoon, drivers behind him can activate their automated driving system. The following vehicles merely replicate the dynamic driving tasks of the lead vehicle, which facilitates their driving environment considerably. Vehicle-to-vehicle communication technologies are used to transfer the control signals. Therefore, at least connected vehicles are required for such mixed-traffic scenarios (Mahmassani, 2016).

A literature review on recent contributions to the planning of truck platoons is given by Kishore Bhoopalam et al. (2017). Most of the known platooning models concern long-haul traffic, as in the formulation given by Larsson et al. (2015). Maiti et al. (2017) provide an ontological framework for ad-hoc platoon formations. First ideas of using their advantages in an urban context are proposed by Agatz et al. (2016) with the related concept of flexible road trains. The design of dedicated AV zones, where platooning is especially desired by traffic authorities, is evaluated by Chen et al. (2017).

3. Service network design for autonomous vehicles in platoons

In this section, we introduce the SNDAVP and state its mathematical model. The description focuses on our contributions to familiar models in the research field of service network design.

3.1. Problem definition

SNDAVP addresses the design of a service network for the first tier of city logistics. Due to regularity in the demand, we are able to occupy a tactical perspective. Goods appear in external zones and need to be transported to satellites, where demand originates from. At first, the physical network $G^{ph} = (N^{ph}, A^{ph})$ is considered with nodes representing the locations of external zones as well as satellites. Arcs connect the nodes in the Euclidean space. To synchronize formations of platoons and their individual vehicles in a reasonable manner, we not only consider the spatial location of facilities but also time as an additional dimension.

To form the time-expanded network $G = (N, A)$, we replicate each node in discrete time steps $t \in T = \{0, \dots, T_{max}\}$ for a given planning horizon T_{max}. Nodes $i \in N$ either belong to subset N_E for external zones or N_S for satellites, while $N^-(i)$ and $N^+(i)$ mark preceding and succeeding nodes. The time-expanded network includes three types of arcs $(i, j) \in A$. Holding arcs link the same physical representatives of external zones in different time periods as unloading arcs do for satellites. Movement arcs allow for traveling in space and time between nodes.

Using this time-expanded network, goods $d \in D$ with volume $v(d)$ have to be transported from their assigned external zone $e(d) \in N_E$ to a given satellite $s(d) \in N_S$. In our deterministic model, we assume that goods have to be picked up from external zones in the time period they appear. Since synchronization with the second tier is required, delivery to satellites is enforced strictly for the time period requested.

Services $r \in R$ are performed by capacitated vehicles of the fleet to fulfill demand in a repetitive manner and consist of a sequence of service legs. A service leg describes a transportation move of a vehicle on an arc between two nodes. Based on the assumption of a mixed autonomous fleet, we differentiate between two types of services depending on the vehicle type. Manually operated vehicles (MVs) are driven by humans and can travel on all available arcs of the network. Autonomous vehicles (AVs) do not contain a driver and can only move freely in specific AV zones that are distinguished by a subset of arcs $A_A \subset A$. Platooning is an additional property that an MV service can provide and an AV can use. AVs can follow an MV via platooning on any given arc it performs a service on. With the guidance of a leading MV, an AV can travel on parts of the network it could not reach autonomously. SNDAVP serves as a framework for synchronization of vehicles in space and time to form platoons.

The time-expanded network consists of two layers. The first layer contains the entire network for MV services $r \in R_M$. The second layer is reserved for AV services $r \in R_A$ and thus, the network is limited. Platoons can move just like individual MVs but further allow for AVs to merge or split and thereby connect the two layers. Figure 1 shows a simple example of services displayed in the physical and two-layer time-expanded network.

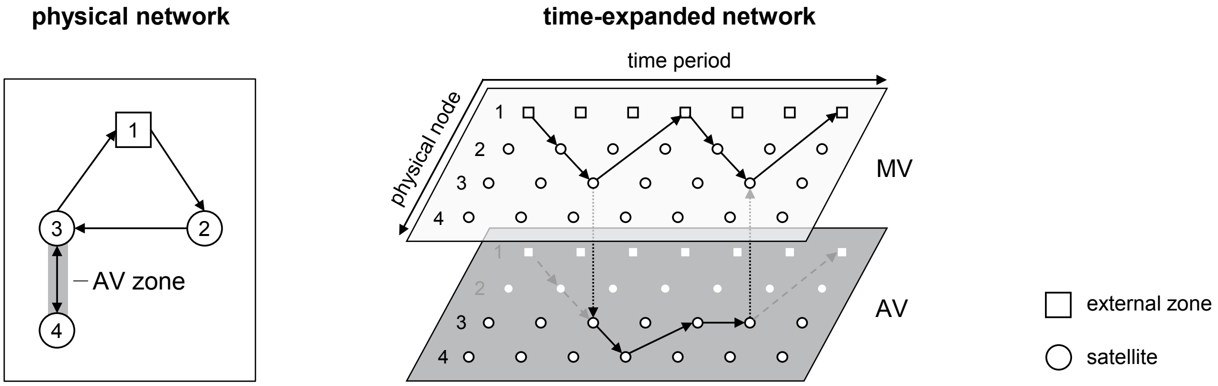

Figure 1: physical network and corresponding time-expanded network with two layers

One MV visits two satellites on a repetitive service and one AV is able to travel between satellites 3 and 4. After loading simultaneously in external zone 1, the AV follows the MV to reach its feasible area, forming a platoon with extended capacity. It splits at satellite 3 and rejoins at the same place in the next iteration of the MV service. In the meantime, it delivers to satellite 4 but has to wait for one time period to merge with the platoon.

3.2. Mathematical formulation

We formulate the SNDAVP model as a mixed integer linear program (MILP) based on the UVSND formulation proposed by Crainic and Sgalambro (2014). Further insights into asset management were gathered from Andersen et al. (2009) and Crainic et al. (2014). Starting with the traditional fixed charge capacitated multicommodity network design (CMND) formulation, we include decision variables for the selection of services. Finally, we add control of the vehicles in the fleet and especially the platoon formations. Both flow and design variables are arc-based in the following formulation.

$$\min \sum_{r\in R}\left[f_r\phi_r + \sum_{(i,j)\in A}\left[k_{ijr}y_{ijr} + a_{ijr}p_{ijr} + \sum_{d\in D} c_{ij}^d x_{ijr}^d\right]\right] \tag{1}$$

$$\text{s.t.} \quad \sum_{r\in R}\sum_{j\in N^+(i)} x_{ijr}^d - \sum_{r\in R}\sum_{j\in N^-(i)} x_{jir}^d = \begin{cases} v(d), & i = e(d) \\ -v(d), & i = s(d) \\ 0, & i \neq e(d), s(d), \end{cases} \qquad d\in D,\ i\in N \tag{2}$$

$$\sum_{d\in D} x_{ijr}^d \le y_{ijr}u_M + p_{ijr}u_A, \qquad (i,j)\in A,\ r\in R_M \tag{3}$$

$$\sum_{d\in D} x_{ijr}^d \le y_{ijr}u_A, \qquad (i,j)\in A_A,\ r\in R_A \tag{4}$$

$$\sum_{(i,j)\in A:\, t(i)\le t<t(j)} y_{ijr} - \phi_r \le 0, \qquad t\in T,\ r\in R \tag{5}$$

$$\sum_{j\in N^+(i)} y_{ijr} - \sum_{j\in N^-(i)} y_{jir} = 0, \qquad i\in N,\ r\in R_M \tag{6}$$

$$\sum_{j \in N^+(i)} y_{ijr} - \phi_r = 0, \qquad i \in N_E: t(i) = 0,\ r \in R_M \tag{7}$$

$$\sum_{r \in R_M} \sum_{j \in N^-(i)} p_{jir} + q_{h^-(i)i} = \sum_{r \in R_M} \sum_{j \in N^+(i)} p_{ijr} + q_{ih^+(i)}, \qquad i \in N_E \tag{8}$$

$$\sum_{j \in N^-(i)} \left[\sum_{r \in R_M} p_{jir} + \sum_{r \in R_A} y_{jir} \right] = \sum_{j \in N^+(i)} \left[\sum_{r \in R_M} p_{ijr} + \sum_{r \in R_A} y_{ijr} \right], \qquad i \in N_S \tag{9}$$

$$\sum_{(i,j) \in A:\, t(i) \le t < t(j)} \left[\sum_{r \in R_M} p_{ijr} + q_{ij} \right] \le \sum_{r \in R_A} \phi_r, \qquad t \in T \tag{10}$$

$$p_{ijr} \le y_{ijr} n_P, \qquad (i,j) \in A,\ r \in R_M \tag{11}$$

$$\sum_{r \in R_M} \phi_r \le n_M, \tag{12}$$

$$\sum_{r \in R_A} \phi_r \le n_A, \tag{13}$$

$$\phi_r \in \{0,1\}, \qquad r \in R \tag{14}$$

$$p_{ijr} \ge 0, \qquad (i,j) \in A,\ r \in R_M \tag{15}$$

$$p_{ijr} = 0, \qquad (i,j) \in A,\ r \in R_A \tag{16}$$

$$q_{ij} \ge 0, \qquad (i,j) \in A \tag{17}$$

$$x_{ijr}^d \ge 0, \qquad (i,j) \in A,\ r \in R,\ d \in D \tag{18}$$

$$y_{ijr} \in \{0,1\}, \qquad (i,j) \in A,\ r \in R \tag{19}$$

Objective function (1) minimizes overall costs. Fixed costs f_r are associated with the selection of a service using ϕ_r and costs k_{ijr} with each service leg, where y_{ijr} is activated. The respective flow of transported goods x_{ijr}^d on a service leg induces cost c_{ij}^d. The cost factor a_{ijr} has to be applied to the number of AVs (p_{ijr}) that follow an MV on a service leg. This is necessary, because, while no additional services are established, platooning vehicles still use resources. Constraints (2) assign supply to external zones and demand to satellites or conserve flow of goods through transit nodes. Additionally, transshipment of goods between services is allowed. Transported goods have to fulfill capacity constraints (3) on each leg of a service. Capacity u_M of an MV can be extended by a constant value u_A for each additional AV in the platoon. For AV services, constraints (4) limit movements to feasible arcs and restrict capacity. Constraints (5) ensure that a specific service leg is assigned to just one service during one point in time, which is queried by function $t(i)$.

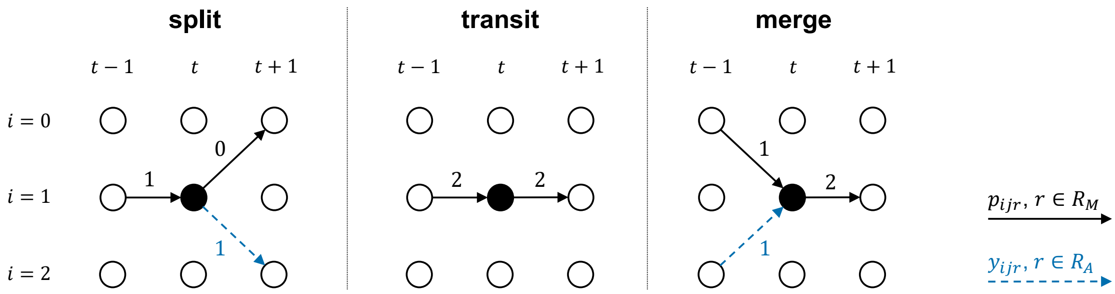

Figure 2: platoon operations

For the controlled case, each MV service should perform circular routes within the given planning horizon. Constraints (6) prevent the splitting of routes between service legs, while constraints (7) set the same external zone as both start and end node of any selected MV service. Each node of the time-expanded network is subject to flow conservation constraints that balance the incoming and outgoing number of AVs. The number of AVs following an MV service via platooning (p_{ijr}) or staying idle at an external zone (q_{ij}) is conserved by constraints (8). Function $h(i)$ displays replications of an external zone in preceding ($h^-(i)$) or succeeding ($h^+(i)$) time periods, which are connected by holding arcs. In satellites, conservation of platoon flow is ensured by (9).

Figure 2 states examples for the three basic platoon operations. Using feasible arcs, AVs can either split from a platoon when initiating a service or merge to a platoon after finishing a service. A platoon, which is already formed, can transit through any node of the network while keeping the number of following AVs steady. Switching between platoons is also allowed by combining split and merge operations. To enable for those operations, constraints (6) and (7) are not applied to AV services. For platooning, only the number of selected AVs can be utilized during each time period due to (10). Constraints (11) limit the allowed number n_p of platooning AVs per activated MV service leg. In terms of asset management, the number of activated services is restricted in (12) and (13) to prescribed numbers of available vehicles per type n_M and n_A. AVs are only allowed to follow MVs by platooning due to (15) and (16), while the remaining constraints define variable types.

4. Computational experiments

In this section, we prove functionality of the SNDAVP model and evaluate potential savings by using mixed autonomous fleets. Since the problem is computationally hard, small problem instances are examined that are tractable for the commercial solver. A simple physical network with feasible connections only between neighboring nodes is used. As displayed in Figure 3, the 2 external zones and 6 satellites are symmetrically located in an orthogonal grid with a travel time of one time period per link. If the travel time towards a given node exceeds one time period, the service route has to pass through nodes in between. We make this assumption because satellites should at best be distributed within the city area and easily accessible for freight traffic.

In all instances, a planning horizon of 4 h is considered. In the respective time-expanded network, nodes are replicated in time periods of 15 mins. 12 goods with individual volumes ranging from 1 to 5 units need to be distributed to their randomly assigned satellite in an appointed time period. To better explain the effects of same day delivery, we use different demand patterns. The first one represents a conventional next day delivery (NDD) approach, where all of the supply for the 4 h planning horizon is released in the first time period at the external zones. In the second pattern resembling same day delivery (SDD), goods appear at a random external zone exactly 1 h ahead of their promised arrival time at the satellite. This demand pattern poses challenges for vehicles and their services. With more returns to external zones, presumably shorter tours are performed and less capacity per vehicle is needed. Two different types of vehicle configurations are tested. In the conventional homogeneous fleet, solely MVs with a capacity of 20 volume units are utilized. The mixed autonomous fleet contains MVs and AVs, each having a capacity of 10 volume units. This embraces the notion of using platoons to extend load capacity as required. The number of available AVs is restricted to 3, as is the maximum number of following AVs in a platoon.

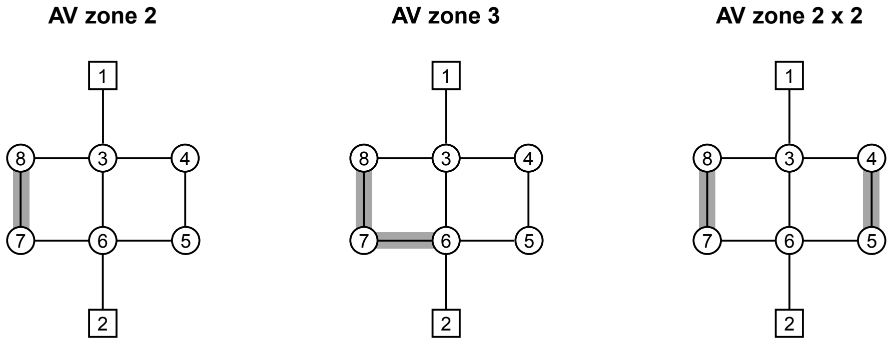

Figure 3: examined AV zone configurations

Costs for selecting a service differ between the two vehicle types. Since AVs do not need a driver, labor costs of 20 per hour can be neglected for the whole 4 h shift. We therefore set fixed costs $f_r = 100$ for MVs and $f_r = 20$ for AVs. Costs k_{ijr} for service legs are 2 for movement arcs, 1 for unloading arcs at satellites and 0 for holding arcs at external zones. A platooning vehicle costs $a_{ijr} = 1$ per service leg, while one volume unit of a transported good is associated with $c_{ij}^{d} = 0.1$.

We denote 3 types of AV zone configurations to evaluate the efficacy of AV services. Only in those zones highlighted in Figure 3, AVs can drive autonomously in both directions while they have to use platooning to move on the rest of the network. The first configuration contains only one arc between 2 satellites, the second one connects 3 satellites using 2 arcs. In the third configuration, there are 2 AV zones with 2 connected nodes each. Idling by using a holding arc is allowed at any satellite with AVs acting as a temporary storage facility.

The described instances are solved with CPLEX 12.6.2 using Concert Technology in C++. On each run, a time limit of 2 h is imposed. Table 1 displays the evaluated costs and CPU times for the 8 demand instances with 4 AV zone configurations each. For instances with AV zones that were not solved within the time limit, the remaining gap is listed. The results show that a mixed autonomous fleet is able to reduce service costs considerably. Moreover, runtimes for solving the problem to optimality increase significantly compared to the basic variant without any AVs. NDD instances appear to consume even more time than SDD instances, because longer durations between origin and destination nodes allow for more routes to choose from. In general, we suspect AV services to be responsible for longer runtimes. While they are restricted to certain zones, they do not have to be circular as MV services are, which start and end at the same external zone. Additionally, the solution space increases due to the multitude of possibilities to synchronize vehicles to form platoons.

Table 1: computed results for next and same day delivery instances with different AV zone configurations

	no AV zone			AV zone 2			AV zone 3			AV zone 2 x 2		
instance	cost	CPU time	gap	cost	CPU time	gap	cost	CPU time	gap	cost	CPU time	gap
ndd_0	342	1,118 s	-	298	152,706 s	6.91%	302	71,497 s	4.08%	299	70,472 s	3.04%
ndd_1	344	1,903 s	-	307	97,963 s	13.06%	280	103,154 s	4.78%	281	122,414 s	4.97%
ndd_2	335	1,116 s	-	299	96,709 s	5.84%	294	64,386 s	3.49%	294	84,309 s	3.46%
ndd_3	345	15,435 s	-	330	113,532 s	4.08%	328	97,554 s	3.75%	341	94,045 s	8.98%
sdd_0	562	630 s	-	494	31,569 s	-	487	42,372 s	-	494	41,702 s	-
sdd_1	567	3,703 s	-	453	110,810 s	-	428	35,250 s	-	452	78,205 s	-
sdd_2	456	1,597 s	-	398	26,242 s	-	398	27,257 s	-	399	38,174 s	-
sdd_3	565	2,117 s	-	512	122,184 s	-	488	90,472 s	-	513	171,728 s	2.63%

Table 2: average costs, savings, service legs changed and number of utilized vehicles for next and same day delivery

demand pattern		no AV zone	AV zone 2	AV zone 3	AV zone 2 x 2
NDD ⌀	cost	341.50	308.50	301.00	303.75
	savings	-	9.66%	11.86%	11.05%
	service legs changed	-	22.40%	26.56%	33.85%
	number of MVs	3.00	2.00	2.00	2.00
	number of AVs	-	2.25	2.00	2.00
SDD ⌀	cost	537.50	464.25	450.25	464.50
	savings	-	13.63%	16.23%	13.58%
	service legs changed	-	19.61%	22.27%	28.13%
	number of MVs	4.75	3.50	3.50	3.50
	number of AVs	-	2.00	1.50	1.75

Table 2 outlines average results for both the instance sets NDD and SDD of each AV zone configuration. It contains costs, savings and changed service legs compared to the scenario without AVs, as well as numbers of utilized vehicles per type. To fulfill demand of SDD instances, more vehicles than for NDD instances are needed, which leads to higher overall costs. By introducing AV zones, overall costs can be lowered significantly. This is despite the fact that optimality for most solutions is not proven. Achieved savings compared to the conventional fleet are relatively larger for SDD. Service legs changed measures the percentage of transportation moves between nodes that changed based on the original solution without AVs. The results show that a mixed fleet with AVs produces different itineraries than a homogeneous fleet with MVs only.

With AV zone 3, the lowest costs are achieved in most instances. Since it is the only setup, in which AVs can reach 3 nodes coherently, this is not overly surprising. The achieved cost savings can clearly be associated with the reduced number of MVs. Although AVs can only drive in restricted zones, 2 AVs can substitute 1 MV including driver in most configurations. In general, platooning proves to be useful in providing MVs with extra capacity on demand. By inspecting individual solutions, we further notice benefits from using AVs as temporary storage facilities in satellites outside of AV zones.

5. Conclusions and future work

In this paper, we introduce mixed autonomous fleets into the first tier of city logistics. In the proposed SNDAVP formulation, the difficulty of synchronizing the multiple heterogeneous vehicles is inspected in particular. AVs are able to move driverless in particular zones only, while platooning is firstly utilized as an option to transfer between those zones. This allows service providers to use AVs in urban environments, where some parts of the network are hard to operate by an automated system, providing a first step towards fully automated freight distribution in the future.

Our experiments indicate that mixed autonomous fleets provide potential cost savings when deployed in city logistics. However, the increased complexity of the problem prevents us from solving larger instances to optimality in reasonable time. While some insights into reducing the solution space are gathered from these early experiments, suitable solution algorithms are required to solve real-world scenarios appropriately. Same day delivery entails shorter – if any – lead time to plan logistics operations ahead. Tactical planning models like the SNDAVP are challenged to adopt this trend by considering stochastic demands and targeting robust rather than optimal solutions. Deeper evaluations of AV zone configurations and the search for advantageous urban network layouts for AVs further pose interesting questions for future research.

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