Facility and dynamic fare design for multimodal automated vehicle logistics system under traffic flow constraints

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1 Introduction

Automated vehicle logistics systems (AVLSs), which utilize *automated vehicles (AVs)* for freight transportation on roads, are expected to significantly reduce operating costs for long-distance transport and enhance efficiency compared to conventional manned systems (Marzano *et al.*, 2022). However, in the near future, the operational area (*ODD: operational design domain*) for such AVs will be still limited to designated areas such as dedicated lanes on highway, and thus AV-only logistics system will not work alone. To fill the gap, multimodal logistics systems that combine AVs for long-distance transport on highway and manned *regular vehicles (RVs)* for last-mile transport on arterial roads could be promising.

The operation of such multimodal logistics systems requires *logistics hubs* where cargo can be transfered between AVs and RVs. Designing these hubs (e.g., determining their locations, maximum transfer flow, and maximum storage volumes) is essential for optimizing the system. For this design, the impact of these systems on general traffic flow must be also considered, as roads have limited capacity and are shared with general traffic that has unique temporal and spatial distribution patterns (e.g., logistic vehicles need to avoid morning peak hours). Although several studies have proposed hub optimization problems for conventional multimodal logistics systems (Yamada *et al.*, 2009, Teye *et al.*, 2017), no studies have investigated this issue on AVLS.

Fare design for such logistic systems is also important (Holguín-Veras & Aros-Vera, 2015). This is because, in general, carriers (operators of AVs and RVs) and consignors (cargo owners) seek their own profit, and thus their behaviors will not be socially optimal if fare was not appropriate. In order to facilitate efficient usage of logistic hubs and avoidance of traffic congestion, the authority need to determine proper fare that changes dynamically depending on traffic conditions.

This study proposes novel methodology for optimal design of *multimodal AVLS (M-AVLS)*. It jointly optimizes logistics hubs' location and size, dynamic fare for carriers and consignors, and operation plan for both of AVs and RVs, considering the specific issues in M-AVLS such as traffic flow constraints, to minimize the social cost. It is noteworthy that, while the proposed methodology is able to derive numerical solutions of M-AVLS under specific scenario conditions, it also yields general theoretical properties of M-AVLS that could have important policy implications. To the authors' knowledge, no existing studies have proposed such optimization methods for M-AVLS.

2 Methodology

We develop a model of M-AVLS by significantly extending the model of shared automated vehicle system for passengers proposed by Seo & Asakura (2022), Seo *et al.* (2024). The key problem setting and assumptions are as follows. The road network consists of three parts: AV-only parts, RV-only parts, and logistic hubs. A typical network structure is shown in Fig. 1.

In this network, three agents travel: AVs, RVs, and cargo. AVs and RVs travel the corresponding roads. Cargo can travel the road only if it is carried by AVs or RVs, and can be transfered at logistics hubs. The time-dependent origin-destination demand of cargo is given, and the system must fulfill it. AVs and RVs circulate the network for a given operation duration; they may transport cargo arbitrary times.

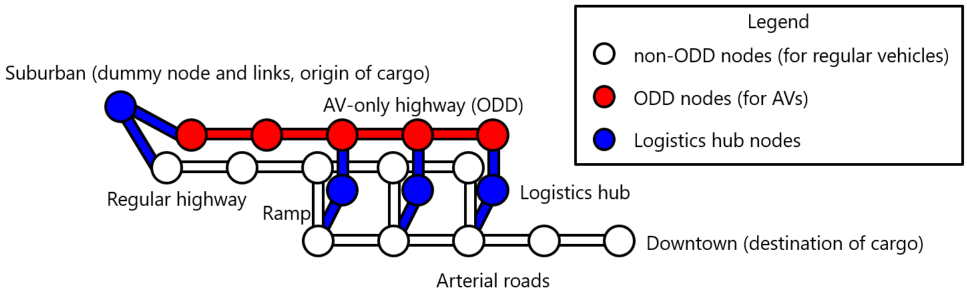


Figure 1 – *An example of road network. It consists of highway with RV-lane and AV-lane, arterial road, and logistics hubs that transfer cargo between AVs and RVs.*

We consider dynamical flow on this network. Each of nodes and links has specific capacity, representing traffic flow capacity, vehicle queuing capacity, and cargo transfer/storage capacities. On the road, the capacity changes dynamically considering the background traffic of general vehicles with a given pattern.

We assume that AVs, RVs, and consignors (cargo owners) seek their own profit. They determine their route individually to maximize their generalized operation/transportation balance, which is the weighted sum of vehicle operation cost, travel time cost (for vehicles), destination arrival time cost (for cargo), fare charged (for both of vehicles and cargo), and revenue (for vehicles).

Under the above assumptions, we formulate an optimization problem termed [DSO-M-AVLS] (DSO stands for dynamic system optimal). The decision variables are dynamical flow of AVs, RVs, and cargo, capacity of logistics hubs, the total number of AVs and RVs, fare charged for cargo when using specific AVs, RVs, and hubs, and fare charged for AVs and RVs when using specific roads. The objective function is the social cost which is the weighted sum of total distance traveled by vehicles, hub construction costs, and others. The problem is formulated as a variant of the minimum cost flow problem, extended by a point-queue-based dynamic traffic model. It is guaranteed that the optimal solution of [DSO-M-AVLS] minimizes the social cost, while each agent minimizes their own private cost considering the fare. This was done by adopting the mathematical framework proposed by Akamatsu & Wada (2017), Seo *et al.* (2024).

3 Results

3.1 Theoretical properties

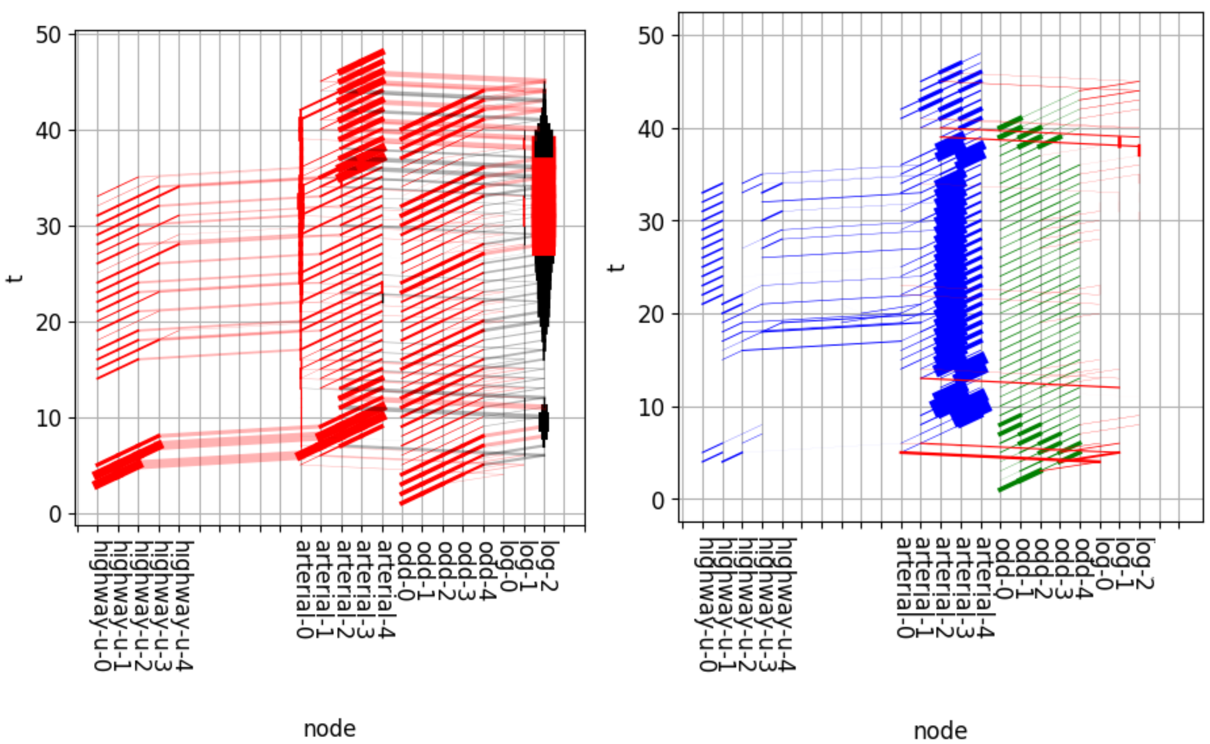
By analyzing the formula and the optimality conditions of [DSO-M-AVLS], we derive several important theoretical properties on M-AVLS. Specifically, the following properties are proven as mathematical theorems for the solution of [DSO-M-AVLS]:

1. System optimal: The solution minimizes the social cost.

2. User equilibrium for carriers: All RVs experience the same balance (revenue minus generalized operation cost). Similarly, all AVs experience the same balance.
3. User equilibrium for consignees: All cargo with the same properties (i.e., origin, destination, desired arrival time to the destination) experience the same generalized cost.
4. For a consignee, a fare is charged only when they uses a vehicle or hub operating at full capacity.
5. For a carrier, a fare is charged only when they uses a road operating at full capacity.
6. Consignees may need to pay fare to carriers when their cargo is transported by vehicles, and to hub owners when it is transfered/stored at hubs.
7. Carriers may need to pay fare to road owners.
8. The balance of carriers for one series of operation is always zero.
9. The construction cost (i.e., depreciation expense for the considered period) of logistics hubs is fully covered by the fare income from cargo.

The properties 1–3 are rephrase of the properties explained in Section 2. The properties 4 and 5 state that fare is charged only if negative externality exists. The properties 6 and 7 clarify the flow of money in M-AVLS. Note that the fare in this study is a kind of tax and different from the service fee for profit; in this study, the service fee is not considered for the sake of simplicity. The properties 8 and 9 might have significant policy implications. They mean that the optimal logistics fleet and hubs can be prepared by taking proper fare from users. In fact, they can be considered the logistics equivalent of the "self-financing principle", a concept in transport economics that states the construction cost for optimal road capacity can be covered by congestion pricing (Verhoef & Mohring, 2009).

3.2 Numerical examples



(a) *Cargo flow*

(b) *Fare charged for cargo*

Figure 2 – *Spatial-temporal distribution of flow and fare.*

To demonstrate the behavior of [DSO-M-AVLS] quantitatively, it was solved for the hypothetical toy network shown in Fig. 1. It consists of 5-node highway and 5-node arterial road, connected by 3 ramps and logistics hubs. All cargo need to be transported from the suburban to the downtown. The time duration was set to 50 timesteps. Timesteps from 15 to 35 were assumed as peak periods; during the period, the traffic capacity for RVs was reduced to represents traffic flow constraints imposed by the background general vehicles.

The optimal solution is visualized as Fig. 2. It shows spatial-temporal flow of cargo and distribution of fare charged for them. The vertical axis mean time: the upper is the future. The horizontal axis represents the location (node): the arrangement of nodes is similar to Fig. 1, with the right side being closer to downtown for each type of road.

The width of each line represents the amount of flow or fare. For example, in Fig. 2a, the lines extending from node "highway-u-0" on timestep 4 to the upper right direction represent the movement of cargo from the suburban to the downtown-direction on highways, and they are transfered to arterial roads (node "arterial-0") to reach the downtown (node "arterial-4"). Similarly, the vertical lines at node "log-2" represents the amount of cargo stored at the logistics hub near the downtown on each timestep. The red lines in Fig. 2a represents flow that reaches the capacity. The line color in Fig. 2b represents recipient of the money: blue means RVs, green means AVs, and red means hubs.

In Fig. 2, several reasonable behaviors can be confirmed. According to Fig. 2a, during the peak period (15–35 timesteps), cargo flow on arterial roads (transported by RVs) was smaller due to traffic capacity constraints. Thus, cargo was stacked up at the logistics hub "log-2" until the peak period ended. On AV-only lane on highway ("odd-0" to "odd-4"), cargo flow was not affected by the peak period as AVs were independent from the other traffic.

According to Fig. 2b, fare was mostly charged to arterial road transfer during the peak period; this is reasonable as only a limited amount of cargo can reach the downtown during the peak period, which makes them competitive. Not much fare was charged for hub usage under this particular scenario parameters, but some fare was charged before and after the peak period, representing high demand of transfer. Note that the optimal hub capacity was largest at the hub nearest to downtown.

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