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► **To cite this version:**

Sahar Bsaybes, Alain Quilliot, Annegret K Wagler. Fleet management for autonomous vehicles using multicommodity coupled flows in time-expanded networks. 17th International Symposium on Experimental Algorithms (SEA 2018), Leibniz International Proceedings in Informatics (LIPIcs), 2018. hal-02045789

HAL Id: hal-02045789

<https://hal.science/hal-02045789>

Submitted on 22 Feb 2019

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Fleet management for autonomous vehicles using multicommodity coupled flows in time-expanded networks

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Abstract. VIPAFLEET is a framework to develop models and algorithms for managing a fleet of Individual Public Autonomous Vehicles (VIPA). We consider a homogeneous fleet of such vehicles distributed at specified stations in a closed site to supply internal transportation, where the vehicles can be used in different modes of circulation (tram mode, elevator mode, taxi mode). We treat in this paper a variant of the Online Pickup-and-Delivery Problem related to the taxi mode by means of multicommodity coupled flows in a time-expanded network and propose a corresponding integer linear programming formulation. This enables us to compute optimal offline solutions and to apply the well-known meta-strategy Replan to the online situation. As it turned out that Replan requires too long computation times, we devise a heuristic approach h-Replan based on the flow formulation. Finally, we evaluate the performance of Replan and h-Replan in comparison with the optimal offline solutions, both in terms of competitive analysis and computational experiments, showing that h-Replan computes reasonable solutions, so that it suits for the online situation.

1 Introduction

The project VIPAFLEET aims at contributing to sustainable mobility through the development of innovative urban mobility solutions by means of fleets of Individual Public Autonomous Vehicles (VIPA) allowing passenger transport in closed sites like industrial areas, medical complexes, campuses, or airports. This innovative project involves different partners in order to ensure the reliability of the transportation system [10]. A VIPA is an autonomous vehicle that does not require a driver nor an infrastructure to operate. It is developed by Easymile and Ligier [8, 9] thanks to innovative computer vision guidance technologies [13, 14], whereas the fleet management aspect is studied in [?].

A fleet of VIPAs shall be used in a closed site to transport employees, customers and visitors e.g. between parkings, buildings and from or to the restaurant at lunch breaks. The fleet is distributed at specified stations within the

site. To supply internal transportation, a VIPA can operate in three different transportation modes:

- *Tram mode*: VIPAs continuously run on predefined cycles in a predefined direction and stop at a station if requested to let users enter or leave.
- *Elevator mode*: VIPAs run on predefined lines and react to requests by moving to a station to let users enter or leave, thereby changing their driving direction if needed.
- *Taxi mode*: VIPAs run on a connected network to serve transport requests (from any start to any destination station within the network within given time windows).

This leads to a Pickup-and-Delivery Problem (PDP) under special constraints in a metric space encoding the considered closed site, where a fleet of servers shall transport goods or persons from a certain origin to a certain destination. If persons have to be transported, we usually speak about a Dial-a-Ride Problem. Many variants are studied in the literature, including the Dial-a-Ride Problem with time windows [4, 5]. In our case, we are confronted with an online situation, where transportation requests are released over time [1–3]. Problems of this type are known to be \mathcal{NP} -hard, see e.g. [12], which also applies to the problem variant considered here, see Section ?? for details.

In [?], we focus on the economic aspect of the problem where the objective is to minimize costs; several algorithms are presented and evaluated w.r.t. minimizing the total tour length for the tram and elevator mode that handle the requests coming online, solve a PDP, and generate tours for the VIPAs in order to serve the transport requests.

The taxi mode is the most advanced circulation mode for VIPAs in the dynamic fleet management system. The transport requests are released over time and need to be served within a specified time window. Due the time windows, it is not always possible to serve all transport requests (e.g., if more requests are specified for a same time window than VIPAs are available in the fleet). Hence, the studied PDP is an admission problem as it includes firstly to accept/reject requests and secondly to generate tours for the VIPAs to serve the accepted requests. We are confronted with both the quality-of-service aspect of the problem (with the goal to accept as many requests as possible) and the economic aspect (with the goal to serve the accepted requests at minimum costs, expressed in terms of minimizing the total tour length of the constructed tours), see again Section ?? for details.

In [?,?], a variant of the PDP is studied where the tours are supposed to be nonpreemptive and at each time, (at most) one customer can be transported by a VIPA (note: one customer can be a group of people less than the capacity of the VIPA), and a VIPA cannot serve other requests until the current one is delivered. This leads to a load non-preemptive DARP with time windows or PDPTW and server capacity 1, where the goal is to accept as many requests as possible and to find a tour of minimal length to serve all accepted requests.

In order to solve this problem, three approaches are considered:

- a simple heuristic, the Earliest Pickup Heuristic, that incrementally constructs tours by always choosing from the subsequence $\sigma(t')$ of currently waiting requests this request with smallest possible start time and appending it to the tour with shortest distance from its current end to the requested origin;
- the two well-known meta-strategies Replan and Ignore (which are proposed in [?] for the ??? problem and can be applied to any online problem in time-stamp model, see e.g. [?, ?, ?]) that determine which requests from $\sigma(t')$ can be accepted, and compute optimal (partial) tours to serve them, where
 - Replan performs these tours until new requests are released, but
 - Ignore completely performs these tours before it checks for newly released requests.

It is natural to interpret the PDPTW by means of flows in a time expanded network [7, 11] as, e.g., proposed by [6] for PDPTW. In this work, we propose an approach for the taxi mode by flows in time expanded network where one request can be handled at a time by a vehicle and

- the time windows of the requests are restrictive so that if a customer wants to be picked up from a station u at time t^u and delivered at station v at time t^v where the shortest distance between u and v is $d(u, v)$ we have precisely $t^u + d(u, v) = t^v$,
- the time windows of a request are large so that there is an interval of time (tight or not) when the customer can be picked up and another when the customer can be delivered and $t^u + d(u, v) \leq t^v$.

Based on these criterias, we model the taxi mode of the dynamic fleet management system with time windows which allow us to solve a max-profit flow problem to balance the profit of accepted requests against the cost for serving them, see Section 3.

The constraint matrix of the resulting integer linear programming formulation is totally unimodular. This enables us to compute optimal offline solutions easily since the problem turns out to be polynomial in case the capacity of the vehicle is equal to one and the time windows are restrictive. This is not the case for the large time windows even with a vehicle capacity equal to 1, see Section 3. We, then, devise an approach based on the integer linear programming formulation and show experimentally that it computes reasonable solutions, so that it suits the online situation, see Section 4. We close with computational results and a discussion on the pros and cons of our approaches and future lines of research.

maybe remove this since we don't model this in detail but we put a note at the of the IP for restrictive time windows

change this part after finalizing the second model, check whether we propose a heuristic for large time windows or still the computation time is reasonable...

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