Two-echelon Multi-trip Vehicle Routing Problem with Synchronization for An Integrated Water- and Land-based Transportation System

Karademir, C.; Alves Beirigo, B.; Negenborn, R.R.; Atasoy, B.

Publication date
2022

Document Version
Final published version

Citation (APA)
Karademir, C., Alves Beirigo, B., Negenborn, R. R., & Atasoy, B. (2022). *Two-echelon Multi-trip Vehicle Routing Problem with Synchronization for An Integrated Water- and Land-based Transportation System*. Abstract from INFORMS Transportation Science and Logistics Workshop , Bergen, Norway.

Two-echelon Multi-trip Vehicle Routing Problem with Synchronization for An Integrated Water- and Land-based Transportation System

Çiğdem Karademir, Breno A. Beirigo, Rudy R. Negenborn, Bilge Atasoy

Dept. of Maritime & Transport Technology, Faculty 3mE, Delft University of Technology
{c.karademir, b.alvesbeirigo, r.r.negenborn, b.atasoy}@tudelft.nl

Technology and globalization have enabled people to purchase a wide range of products online at any time, leading to worldwide e-commerce sales growing 266% between 2014 and 2021 and are expected to increase by 30% through 2024 [1]. The increase in the consumption has not reflected to the different modes of transportation proportionally and the road freight transportation has a share of more than 50% due to its accessibility and perceived cheapness over the years. However, the cost of moving items on roads, especially in metropolitan areas, has been increasing as due to idle times in vehicle operations and customer inconveniences resulting from congestion-related delays. Moreover, sustainable acts, committed by European Union [2], force the authorities, companies, and public to find alternative ways to transport goods, passengers, and waste towards more sustainable and livable cities.

The number of companies developing new logistics systems using new technologies (electric vehicles, autonomous cars, unmanned vessels, drones, etc.) is on the rise as companies seek to reduce costs, increase customer satisfaction, and provide sustainable solutions. The main limitation of these new technologies is the limited capacity they provide in terms of storage space or driving range [3]. However, they can be efficiently used in cooperation with larger vehicles which act as mobile depots or charging stations. The challenge is to design synchronized operations between different type of vehicles in terms of data exchange, cargo flow, time and space.

Inland waterways have been a cheaper and sustainable solution for long-distance transportation but not for city freight logistics in short distances due to the expensive transshipment operations at the terminals where items are transferred to other networks [4]. However, city transportation problems need to be rethought and reformulated regarding new objectives, autonomous vehicles, advanced communication and computational technologies for the future. In order to realize economies of scale in inland waterway transportation, decision-makers should consider the entire network, including all logistics costs, especially the detailed costs associated with transfers [5].

In this study, we aim to explore the benefits of an *integrated water- and land-based transportation* (IWLT) system for waste collection in the city of Amsterdam using autonomous vessels and *light electric freight vehicles* (LEFVs) [6] to reduce congestion related externalities as well as the damage

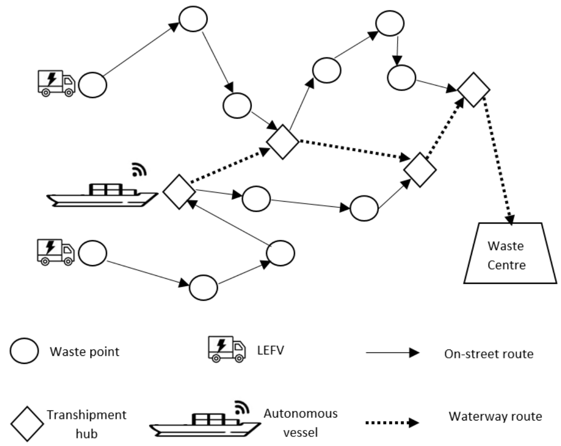

Figure 1: The IWLT network for waste collection.

on fragile quay walls caused by heavy garbage trucks [7]. In this system, autonomous vessels serve as mobile depots for LEFVs that collect on-street garbage. They have relatively low capacities than traditional garbage trucks. Therefore, they need to meet with vessels to empty the collected waste whenever it is best to unload. LEFVs collect waste on the streets and select a waterfront hub to transfer the collected waste to vessels. Synchronizing vessels and LEFVs is further constrained by time windows (collection hours vary per neighborhood) and limited physical space for maneuvering LEFVs and vessels (only a single vessel can access a hub at a time and perform a single transfer task at once). An IWLT system, in addition to reducing heavy vehicle movements, also reduces street traffic with the use of mobile vessels, as there is no need to visit the depot frequently as LEFVs would need to in a road-based system due to their smaller capacity. The problem is modelled as a two-echelon multi-trip vehicle routing problem with time windows, synchronization and one-to-one transfers (2E-MTVRPTW-SS). Unlike most two-echelon models in the literature, which consider a delivery scenario where items are first consolidated and then dispatched, we model a reverse logistics problem (see Figure 1).

The main contributions of this study are thus to:

- Design an IWLT system based on a two-echelon multi-trip vehicle routing problem for waste collection.
- Propose a novel mixed integer linear model for 2E-MTVRPTW-SS with one-to-one transfers at the hubs at a time.
- Provide insights into different collection systems to reduce the issues outlined above based on the realistic case studies developed inspired by the case of Amsterdam.

The IWLT system, where LEFVs and vessels operate in synchronization, is referred to as a two-echelon VRP with flexible vessels system (2E-Flexible) and evaluated with respect to three benchmarks: single echelon VRP with large trucks (1E-Trucks), single echelon VRP with LEFVs (1E-LEFVs), and two-echelon VRP with stationary barges (2E-Stationary) system. It is assumed that larger vehicles (trucks, barges, and vessels) can store at most five full loads of smaller vehicles (LEFVs). These systems are tested on small-sized instances based on mathematical formulations using a commercial solver. The instances are derived from Solomon's VRPTW problems [8], and divided into three categories based on the geographical distribution of the waste points: C type for clustered locations, R for random locations, and RC for randomly clustered locations.

Table 1: Average results for small-sized instances with 10 waste points and four hubs.

		Street Level			Water Level		
		NV	Travel Time	Weighted Avg. Load	NV	Travel Time	Weighted Avg. Load
C	1E-Trucks	1	227,99 (base)	92,11 (base)	-	-	-
	1E-LEFVs	1	392,28 (+72%)	26,52 (-71%)	-	-	-
	2E-Stationary	1	208,65 (-8%)	28,63 (-69%)	1	119,61	79,38
	2E-Flexible	1	181,16 (-21%)	28,19 (-69%)	1	148,24	106,47
R	1E-Trucks	1	277,71 (base)	84,24 (base)	-	-	-
	1E-LEFVs	1,3	413,59 (+49%)	27,61 (-67%)	-	-	-
	2E-Stationary	1	263,82 (-5%)	31,02 (-63%)	1	120,44	86,45
	2E-Flexible	1	205,66 (-26%)	26,65 (-68%)	1	191,28	151,46
RC	1E-Trucks	1	209,88 (base)	136,57 (base)	-	-	-
	1E-LEFVs	2	408,04 (+94%)	38,71 (-72%)	-	-	-
	2E-Stationary^f	2	250,48 (+19%)	42,02 (-69%)	1	62,43	120,63
	2E-Flexible^f	2	197,56 (-6%)	35,91 (-74%)	1	163,58	146,23

Table 1 summarizes the average results of all instances in each type for the problems with ten waste points for all approaches and four hubs for 2E-Stationary and 2E-Flexible systems. For both levels, NV is the number of the vehicles (LEFVs, barges, or vessels), $Travel\ Time$ is the total travel time of the vehicles on their own network, while $Weighted\ Avg.\ Load$ is the weighted average of the load on the vehicles per travel time considering non-empty movements. All instances are solved to optimality except the ones labeled with superscript f, where the best feasible solutions are presented.

The proposed system with synchronized mobile vessels and LEFVs is shown to be a promising solution for the issues with the current system. It can reduce the total travel time of the garbage vehicles on the street by 18% and the weighted average loads of the vehicles by 70% on average across all scenarios without increasing the fleet size of LEFVs significantly even if they have way less capacities than the traditional garbage trucks. The most savings in on-street movements is achieved for R type since mobile vessels can reduce the idle times such as waiting times due to the temporal distances and longer last miles to the waste center due to the spatial distance. Comparing two-echelon systems, the average share of waterway transportation is 46% for 2E-Flexible system and 29% for 2E-Stationary system considering the ratio of time spent on waterways to total time spent on streets and waterways.

The proposed model for 2E-MTVRPTW-SS with one-to-one transfers is a computationally heavy problem. However, the model can be decomposed into sub-problems and used within decomposition-based exact methods or heuristics for larger instances. The gains observed in small instances indicate that potential improvements can be obtained for larger instances. In order to demonstrate the benefits and challenges of such a system in practice, we will apply the proposed modelling approach to real-life waste collection problems in Amsterdam.

Acknowledgement: This research is supported by the project "Sustainable Transportation and Logistics over Water: Electrification, Automation and Optimization (TRiLOGy)" of the Netherlands Organization for Scientific Research (NWO), domain Science (ENW), and by the Researchlab Autonomous Shipping (RAS) at TUDelft. We also thank Marcel Stiphout from the Municipality of Amsterdam for his assistance in designing the two-echelon systems.

References

[1] S. Chevalier, "Global retail e-commerce market size 2014-2023." `https://www.statista.com/statistics/379046/worldwide-retail-e-commerce-sales/`, 2021. Accessed: 2021-10-08.

[2] G. Amsterdam, "Agreements with the city on an emission-free 2025."

[3] S. Yu, J. Puchinger, and S. Sun, "Two-echelon urban deliveries using autonomous vehicles," *Transportation Research Part E: Logistics and Transportation Review*, vol. 141, p. 102018, 2020.

[4] E. Divieso, O. F. L. Junior, and H. C. De Oliveira, "The use of waterways for urban logistics," *Theoretical and Empirical Researches in Urban Management*, vol. 16, no. 1, pp. 62–85, 2021.

[5] B. Groothedde, C. Ruijgrok, and L. Tavasszy, "Towards collaborative, intermodal hub networks: A case study in the fast moving consumer goods market," *Transportation Research Part E: Logistics and Transportation Review*, vol. 41, no. 6, pp. 567–583, 2005.

[6] W. Ploos Van Amstel, S. Balm, J. Warmerdam, M. Boerema, M. Altenburg, F. Rieck, and T. Peters, "City logistics: Light and electric," *Amsterdam University of Applied Sciences, The Netherlands*, 2018.

[7] J. Maes, C. Sys, and T. Vanelslander, "City logistics by water: Good practices and scope for expansion," in *Transport of Water Versus Transport Over Water*, pp. 413–437, Springer, 2015.

[8] M. M. Solomon, "Algorithms for the vehicle routing and scheduling problems with time window constraints," *Operations Research*, vol. 35, no. 2, pp. 254–265, 1987.