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Towards E(lectric)- urban freight: first promising steps in the electric vehicle revolution

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Abstract

Innovative logistics service providers are currently looking for possibilities to introduce electric vehicles for goods distribution. As electrical vehicles still suffer from a limited operation range, the logistical process faces important challenges. In this research we advise on the composition of the electrical vehicle fleet and on the configuration of the service network, to achieve a successful implementation of electric vehicles in the innercity of Amsterdam. Additional question in our research is whether the CO2 emission reduces at all or might even increase due to an increase of tripkilometres as a consequence of mileage constraints by the batteries.

The aim of the implementation of the research is to determine the ideal fleet to transport a known demand of cargo, located at a central depot, to a known set of recipients using vehicles of varying types. The problem can be classified as a Fleet Size and Mix Vehicle Routing Problem (FSMVRP). In addition to the regular constraints that apply to the regular FSMVRP, in our case also time windows apply to the cargo that needs to be transported (FSMVRPTW). The operation range of the vehicles is constrained by the battery capacity. We suggest modifications to existing formulations of the FSMVRPTW to make it suitable for the application on cases with electrical vehicles. We apply the model to create an optimal fleet configuration and the service routes.

In our research case of the Cargohopper in Amsterdam, the performance of alternative fleet compositions is determined for a variety of scenarios, to assess their robustness. The main uncertainties addressed in the scenarios are the cargo composition, the operation range of the vehicles and their operation speed.

Based on our research findings in Amsterdam we conclude that the current generation of electric vehicles as a part of urban consolidation concept have the ability to perform urban freight transport efficiently (19% reduction in vehicle kilometres) and meanwhile have the capability to improve air quality and reduce CO_2-emissions by 90%, and reduce noise nuisance in the inner cities of our (future) towns.

Keywords: Urban deliveries, Commercial electric vehicles, Logistical constraints, CO_2 Emissions, City Logistics Modeling, urban consolidation concept

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Highlights:
Fleet Size and Mix Vehicle Routing Problem with Time Windows (FSMVRPTW) is extended with constraints for electric vehicles, yielding the EVFSMVRPTW problem.
A heuristic is proposed to solve the problem and the model is applied successfully for a case in Amsterdam.
The application shows that a significant improvement in external effects is achieved while the system is still allowed to break even.

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1. Introduction electric urban freight transport

Cities face a number of challenges to remain attractive for inhabitants and visitors. Major problems are pollution, congestion and noise nuisance. At the same time, transportation companies have huge problems to be efficient in urban areas. The OECD (2003) defines urban goods transport as: '*The delivery of consumer goods (not only by retail, but also by other sectors such as manufacturing) in city and suburban areas, including the reverse flow of goods in terms of clean waste*'.

Urban freight transport is a necessary daily activity in and around urban areas. It is a primary support system for retailers to sell their goods, and it makes it possible to satisfy demand of consumers. Therefore, urban goods movement can be regarded as essential for the economic vitality of cities (Muñuzuri et al., 2005). Goods movements represent between 20% and 30% of vehicle kilometres in urban areas, and between 16% and 50% of pollutant emissions by all transport activities (Dablanc, 2007). Although urban freight transport has existed for centuries, this topic has had little attention from public policy makers until the early-nineties. Crainic et al. (2004) argued that this is mainly due to the private character of the urban freight transport sector, while urban freight transport induces many negative externalities. Both the public sector and the private sector have maintained a passive mentality for a long time (Dablanc, 2007).The most important negative externalities are noise nuisance, pollution, unsafe situations and the deterioration of the condition of the infrastructure of cities (Quak, 2008). Muñuzuri et al. (2010) proof that urban freight transport significantly contributes to the total transport-related ecological footprint.

Different stakeholders in urban freight transport (retailers, transport companies, citizens) cause and face different problems (van Duin, 2012), and responsibilities are hard to assign (Lemstra, 2004). Over the years a variety of solutions has been proposed ranging from restricted zones to cleaner vehicles and from coordination transportation to the use of alternative modalities (Geroliminis & Daganzo, 2005). Although the need to solve the problems caused by urban freight transportation is felt by all, successful implementation of solutions is rare. According to Quak (2010) success of urban logistics solutions depend on three factors: logistics, technology and policy; the balance between these three factors will determine the success of the proposed solutions.

Recently attention for electric urban freight transport systems has been growing (Ramsey, 2010). The Electric Vehicle City Distribution (ECLIDIS) projects is one of the first that focussed on distribution centres in European cities and examined the potential for electric trucks to serve urban delivery routes. Despite general claims of success of this program, purchase costs of electric vehicles are still seen as a substantial barrier to widespread implementation (Vermie, 2002). In addition, negative experiences reported by carriers and drivers include vehicle performeance below expectations in terms of range, speed and acceleration, and reliability (Jeeninga et al. 2002). Taniguchi et al. (2000) evaluated a new concept of co-operative use of electric vans for urban freight transport. Their main idea of the system was that an organisation provides some electric vans at various public parking places to be used cooperatively by many companies. Tests were conducted in the central area of Osaka City using 28 electric vans equipped with advanced information systems with the participation of 79 voluntary companies. The results were benefical for residents, drivers, shippers, and freight carriers as the system reduced transport kilometers, improved the sustainable character of Osaka, and alleviated congestion.

Browne et al. (2011) evaluated a trial in which goods dispatched from a suburban London depot were delivered to customers in the City of London. In this trial diesel vans making deliveries direct from the suburban depot to customers in the City of London were replaced by electric vans and tricycles operating from a micro-consolidation centre in the City of London. The results showed that the trial proved successful from the office supplies company's perspective in transport, environmental and financial terms.

Boussier et al. (2011) investigated the effects of congestion created by electric freight vans during the goods delivery. Their research focused on the modelling of the management process of the parking place sharing between car drivers and dedicated areas of goods deliveries. Their model was a part of a multimodal urban traffic simulator based on the paradigm of multi agent system (MAS). The end-user (e.g. city centre Manager) simulates scenarios in agreement with local traffic regulations, the capacity of the fleet and the routing alternatives. With their behavioral models decision makers will be able to select optimal sites for delivering and/or periods for ensuring a good coexistence between all actors of the urban traffic.

Feng and Figliozzi (2013) developed a fleet replacement optimization framework, combined a wide range of scenarios, and used USA market data to find the key economic and technological break even values where Electric Vehicles become competitive against the conventional diesel vehicles. Their results clearly showed that in scenarios with high utilization (over 16,000 miles per year per truck) the electric vehicles are competitive.

Davis and Figliozzo (2013) developed a model which evaluates the implications of routing constraints, route parameters, vehicle characteristics, and ownership costs. They integrated four models: a vehicle ownership cost minimization model, a model to calculate the power consumption and maximum potential range as a function of velocity and weight, a continuous approximation model to estimate fleet size, distance traveled, and ensure that practical routing constraints are satisfied, and a model to estimate the energy needed to travel using real-world travel speed profiles. The main conclusion from their research (Davis & Figliozzi, 2013) was that electric trucks will become competitive only if the cost savings from the reduced operational cost will be sufficient to overcome the significantly higher initial purchase costs.

Our research shows some identical practical circumstances with the above mentioned researches, but differs on essential details. Similar to the study of Browne et al. (2011) the evaluation is compared to the traditional way of distributing. Like the trial in London the inner city of Amsterdam is currently served with traditional vehicles from a neaby depot. In our case we suggest a micro-consolidation centre in the vicinity of the city border. Because of the electrical nature of the vehicles they have a limited operation range and therefore the logistical process provides some challenges to transport cargo into the inner city of Amsterdam. Question in our research is whether the CO2 emission reduces at all or might even increase due to an increase of trip-kilometres as a consequence of mileage constraints by the batteries Whereas Browne et al. (2011) describe an ex-post analysis, we perform an ex-ante analysis based on modelling, as did Boussier et al. (2011). In contrast to the latter, we focus on the re-design of the logistics delivery concept with electric vehicles, i.e. the introduction of an city distribution centre in the current delvery chain e optimize the city distribution concept with electric vehicles for different scenarios in agreement with the local traffic regulations, variations in fleet capacity and in the related service routings.

With the introduction of the city distribution concept with electric vehicles, the Municipality of Amsterdam aims at the realisation of a complex urban distribution objective (DIVV, 2010):

'*Amsterdam strives for a better air quality, road safety, road circulation and less noise nuisance by using smart supply means and ecologically sound transport'*.

This research is carried out as part of the "4C4D: City Distribution" project of Dinalog. In the "4C4D: City Distribution" project important stakeholders in the city distribution field are brought together in order to design smart ideas to improve city logistics (Dinalog, 2011). The stakeholders within this project are for instance knowledge institutes like Delft University of Technology, the Universities of Tilburg and Eindhoven and TNO. Furthermore, private companies are involved such as TNT, Ahold, Peter Appel, TransMission, Binnenstadservice and GreenCityDistribution.

One of the key tasks of the project, treated in this paper, was to advise on the fleet configuration needed for a successful implementation of electric vehicles in Amsterdam's environmental zone. In the next section, we specify the design problem as a Fleet Size and Mix Vehicle Routing Problem with Time Windows (FSMVRPTW), using electric vehicles. Section 3 provides a case description of the inner city of Amsterdam. In Section 4 the scenarios and calculation results are presented. We conclude the paper with a summary of our findings.

2. A mathematical formalisation of FSMVRPTW using electric vehicles

The problem which is the subject of this study is classified as a Fleet Size and Mix Vehicle Routing Problem with Time Windows (FSMVRPTW) (Hoff et al., 2010). The aim of the implementation of electric vehicles is to determine the ideal fleet to transport a known demand of cargo to a known set of recipients with their time-windows using a, to be determined, number of vehicles of varying type located at a central depot. Due to the electrical nature of the vehicles, the operation range of the vehicles is constrained by the battery capacity. Next to that the vehicles are idle for a long time once the battery has ran out. This has implications on the routing of the vehicles and therefore modifications need to be made to existing formulations of the FSMVRPTW to make it suitable for the application on cases with electrical vehicles.

The FSMVRPTW is basically an extension of the problem which in literature is referred to as the Vehicle Routing Problem (VRP). Toth & Vigo (2002) define the 'VRP that calls for the determination of the optimal set of routes to be performed by a fleet of vehicles to serve a given set of customers'. The solution of a vehicle routing problem is a set of routes, each routes is has a number of destinations at which a single vehicle delivers the goods. Each route starts and ends at the depot of the particular vehicle (Toth & Vigo, 2002).

The FSMVRP combines the vehicle fleet composition problem (Etezadi & Beasley , 1983) and the Vehicle Routing Problem. The first authors to take vehicle routing into account while solving fleet composition problems are Golden et al. (1984). In their article they formulate the so-called Fleet Size and Mix Vehicle Routing Problem (FSMVRP).

By combining these problems more properties of the vehicles can be taken into account. The initial problem vehicle fleet composition problem only takes into account the capacity of the vehicles. Whereas the FSMVRP also takes into account vehicle routing and hence constraints with respect to duration of the working day, time windows and the likes can be taken into account. This is elaborated more thoroughly in the remainder of this paragraph.

Hundreds of articles have been written on the subject of VRP, most of them aiming to provide an exact or approximate solution for the problem. Within the literature of city logistics special attention is given to the VRPTW (Time Windows) problems by (Solomon, 1987; Thompson and van Duin, 2003; Quak and De Koster, 2007; 2009; Quereshi et al., 2011; Deflorio et al., 2012). A wide variety of literature has also been written with respect to the subject of FSMVRP. In a survey carried out by Hoff et al. (2010) 95 scientific papers were regarded with respect to fleet composition problems. In these papers different types of the FSMVRP are discussed. For instance, FSMVRP with Time Windows, with Multiple Depots and other applications in industry. Each of these variations of the FSMVRP requires a different type of mathematical formulation of the problem and consequently a different solving methodology.

In literature basically three formulations of the FSMVRP can be found. The first type of formulation is the simplest one and assumes that the variable costs of each vehicle type are the same (Golden et al., 1984). Later, Salhi & Rand (1993) extended this formulation by including a constraint with respect to the maximum travel time of a vehicle. The second type of formulation takes into account variable costs and travel time for each vehicle type. This formulation is given by Osman & Salhi (1996). The third formulation type is presented by Bräysy et al. (2008) and is specially designed for the FMSVRPTW, the handling of time windows. In this formulation each vehicle is defined separately instead of only a vehicle class (Hoff et al., 2010).The formulation of Bräysy et al. (2008) is such a mixed-integer linear programming formulation. The definition of variables are the following:

n = the number of customers

K = total amount of vehicles available

SL = desired service level

f_k = the fixed acquisition costs of vehicle k

c_{ij}^k = cost of travelling a time unit on link (i,j) with vehicle k

e_{ij}^k = cost of travelling a distance unit on link (i,j) with vehicle k

t_{ij} = time to travel between node i and j

d_{ij} = distance to travel between node i and j

q_k = the capacity of a vehicle of type k

D_k = maximum distance vehicle k can travel

S = vehicle independent starting time of working day

E = vehicle independent end time of working day

W = vehicle independent maximum duration of working day

a_i = start time – window of customer i

b_i = end time – window of customer i

s_i = vehicle independent service time of customer i

g_i = demand of customer i

LB_i = lunch break of the driver at customer i

The formulation of Bräysy et al. (2008) uses graph theory to describe the problem. The nodes represent a collection of locations and the arcs are lines or connections between these locations. These arcs can be either directed or undirected (Beasley, 2011). Each node represents a location of a customer to which has a certain demand of cargo to be delivered. The arcs represent the infrastructure network of the particular city the cargo is distributed in. The distribution is carried out by vehicles with a specified capacity. The aim is to design routes between the nodes in such a way that the routing costs are minimised and all the demand constraints and vehicle constraints are satisfied.

Conrad and Figliozzi (2011) recently analysed the Electric Vehicle Routing Problem, a special case of the Vehicle Routing Problem (VRP) that takes into account the limited range of EV's and the impact of recharging speed. This model shows quite some identical formulas to our problem formulation. However, their model considers recharging options at several customers or at depots. Our model will take into account the limited range of the electric vehicles and a service constraint to meet the time windows of the customers.

Let $G=(N,A)$ be a graph where $N = \{0\} \cup \{1, \dots, n\} \cup \{n+1\}$ is the set of all nodes. Within this set of nodes $D = \{1,\dots,n\}$ defines the set of destinations,with $\{0\}$ and $\{n+1\}$ representing the depot (urban distribution center) for the beginning and the end of the tours. Let $V = \{1, \dots, K\}$ is the set of vehicles. $A \subseteq N \times N$ is the matrix that represents the set of travel possibilities between the nodes. From the matrix some travel possibilities are excluded, being$(i,i), (i,0), (n+1,i); i \in n$. This is done to prevent trips from a particular node back to the same node without travelling to another node in between. Furthermore, node 0 represents the beginning of a trip and $n+1$ the end of a trip. The variable x_{ij}^k is a binary decision variable, if vehicle k travels directly from destination i to destination j the value of the decision variable equals 1, otherwise it is 0. A vehicle k is not used, if $x_{0,n+1}^k$ equals 1. With $i \in N$ and $k \in V$ means variable y_i^k the starting time of service at node i if it is served by vehicle k. The variable y is determined by adding the travel time of each link t_{ij} and the service time s_i at a node i to the starting time at the depot y_0^k.

Objective function

The objective function is composed of fixed costs and variable costs. Bräysy et al (2008) reformulate the formulation of Liu & Shen (1999) into the following MILP objective function to solve the FSMVRPTW:

$$\text{MIN} \sum_{k \in V} \sum_{j \in D} f_k x_{0j}^k + \sum_{k \in V} \left(y_{n+1}^k - y_0^k \right) + \sum_{k \in V} \sum_{(i,j) \in A} e_{ij}^k x_{ij}^k \tag{1A}$$

Here the objective function is explained. The first term of the objective function (1A) $\sum_{k \in V} \sum_{j \in D} f_k x_{0j}^k$ describes the fixed costs for all vehicles. These costs are added to the equation in case a vehicle k is active on the link *(0,j)* (This link represents the start of vehicle k from the depot to the first destination *j*).

The second term of the objective function $\sum_{k \in V} \left(y_{n+1}^k - y_0^k \right)$ represents the 'en route'-time. The last term of the objective function $\sum_{k \in V} \sum_{(i,j) \in A} e_{ij}^k x_{ij}^k$ represents the distance dependent variable costs. In this presentation of Bräysy et al. (2008) the time dependent costs of the driver are not taken into account in the objective function. The second term only adds a penalty for the 'en route'-time. Therefore we develop a new formulation in which we also consider the hourly wages by multiplying the 'en route time' by the hourly dependent costs c_{ij}^k. The best solution of the problem is the fleet composition with the least average costs per delivery. The objective function is divided by the equation $\sum_{k \in V} \sum_{j \in D} x_{0j}^k$. This equation represents all orders leaving for a destination j and thus the total costs are divided by the total number of transported orders which yields the average costs per delivery. This results in the following non-linear objective function.

$$\text{MIN} \left(\frac{\sum_{k \in V} \sum_{j \in D} f_k x_{0j}^k + \sum_{k \in V} \sum_{(i,j) \in A} \left(y_{n+1}^k - y_0^k \right) c_{ij}^k + \sum_{k \in V} \sum_{(i,j) \in A} e_{ij}^k x_{ij}^k}{\sum_{k \in V} \sum_{j \in D} x_{0j}^k} \right) \tag{1B}$$

Constraints

Some of the constraints are in line with the constraints formulated by Bräysy et al. (2008). However some dedicated constraints are developed in order to make the formulation suitable for the application to the electrical vehicles and can be found in the constraints (8-10) to the working day of the drivers as well as a constraint on the operation range (11-14):

$$\frac{\sum_{k \in V} \sum_{j \in D} x_{0j}^k}{n} \geq SL \tag{2}$$

$$\sum_{i \in D} g_i \sum_{j \in N} x_{ij}^k \leq q_k, \qquad \forall k \in V \tag{3}$$

$$\sum_{i \in N} x_{ih}^k - \sum_{j \in N} x_{hj}^k = 0, \qquad \forall h \in D, \forall k \in V \tag{4}$$

$$\sum_{j \in N} x_{0j}^k = \sum_{i \in N} x_{i,n+1}^k, \qquad \forall k \in V \tag{5}$$

$$x_{ij}^k(y_i^k + s_i + LB_i + t_{ij} - y_j^k) \leq 0, \qquad \forall\, (i,j) \in A, \forall\, k \in V \qquad (6)$$

$$a_i \leq y_i^k \leq b_i \qquad \forall\, i \in N, \forall\, k \in V \qquad (7)$$

$$\left(y_{n+1}^k - y_0^k\right) \leq W, \qquad \forall\, k \in V \qquad (8)$$

$$y_0^k \geq S, \qquad \forall\, k \in V \qquad (9)$$

$$y_{n+1}^k \leq E, \qquad \forall\, k \in V \qquad (10)$$

$$R_{\,0}^{\,k} = D_k, \qquad \forall k \in V \qquad (11)$$

$$R_{\,i}^{\,k} - R_j^k = x_{ij}^k d_{ij}\,, \qquad \forall k \in V, \forall\, (i,j) \in A \qquad (12)$$

$$R_i^k \geq d_{i,n+1} x_{i,n+1}^k, \qquad \forall\, k \in V, \forall\, i \in C \qquad (13)$$

$$R_0^k \geq \sum_{(i,j)\in N} d_{ij} x_{ij}^k, \qquad \forall\, k \in V \qquad (14)$$

The first constraint that is usually considered in FSMVRP(TW) formulations is the constraint that ensures all destinations {1..n} being served. In literature this constraint requires a service level of 100%. However, due to the large variety of other constraints, especially the time windows, in practice situations might occur that a fleet composition cannot serve all the destinations. Therefore in our case constraint (2) is relaxed to the inequality that the amount of transported orders divided by all possible orders that can be transported is higher than or equal to a certain specified service level.

Constraint (3) ensures that the total demand of all the nodes a vehicle k is visiting shall not exceed the capacity of the vehicle. This demand can be measured in multiple ways, for instance a number of pallets or packages or a specified weight of the cargo.

The next constraint (4) ensures the conservation of flows, which means that no vehicles remain at the destinations. Each vehicle arriving at a location must also leave this location. The number of departs a vehicle makes from the depot should be the same as the number of arrivals the vehicle makes at the depot. This constraint (5) makes sure that all vehicles return to the depot.

The next constraint (6) ensures that arrival time between two consecutive orders for each vehicle k allows for service time, lunch break, travel time of the driver between two consecutive orders (Bräysy et al. (2008)). We made an adjustment for the inclusion of a lunch break (LB_i). To fulfill the time windows of the order, constraint (7) is added. This is different to Bräysy et al. (2008), since we combine the lower and upper bound constraint into one constraint.

Additional constraints are imposed to the working day of the driver. Inequality (7) ensures that the total ‘en route time’ is shorter that the specified duration of a working day (W). Inequality (8) states that the starting time of the service at node 0, the depot, is larger or equal to the starting time of the work day of the driver (S). The same applies for inequality (9) where the driver should be back at the depot before his shift ends (E).

The most important additions to the formulation with respect to the electric vehicles are the additional constraints (11-14), that are related to the maximal operation range of the vehicles due to the use of batteries. These constraints are the following.

Each vehicle k shall not exceed its battery capacity (operation range (D_k)). In order to apply a constraint on the operational limit, the distances driven need to be monitored. Therefore a new variable (R_i^k) is defined as spare distance. The initial spare distance is equal to the maximum operation range of the vehicle which is reflected in constraint

(10). The spare travel distance is determined by subtracting the distance travelled between nodes from the spare travel distance in constraint (11)[1]. The most important battery constraints (13-14) are constraints (13-14). Constraint (13) ensures that the spare distance always will be larger than the spare distance needed to travel back to the depot (13). Constraint (14) guarantees that no trip shall start of which the travel distance exceeds the spare distance of a vehicle.

With these additional constraints the mathematical formulation of the FSMVRPTW can now be applied to cases using electrical vehicles and cases with limitations to working days: the Electrical Vehicle Fleet Size and Mix Vehicle Routing Problem with Time Windows (EVFSMVRPTW). The solution of this problem reaches the desired service level at the lowest possible costs without violating the constraints to which the problem is subjected. Unfortunately, the EVFSMVRPTW is NP-hard and hence cannot be solved to optimality. The FSMVRP and FSMVRPTW are also NP-hard because the additional restrictions only increase the complexity of the problem (Dullaert, Janssens, Sörensen, & Vernimmen, 2002). To solve this problem, three types of solution methods can be distinguished: exact solution methods, heuristics and meta-heuristics. Bradley, Hax & Magnati (1977) propose two exact solving methodologies for the mixed integer program. The *Branch-and-Bound* algorithm partitions the feasible region into smaller subdivisions. The other exact algorithm is the *cutting-planes* algorithm. In the area of metaheuristics Bräysy & Gendreau (2005b) classify metaheuristics in the following categories: *Tabu-search algorithms, genetic algorithms* and *miscellaneous algorithms*. Heuristics applied to Vehicle Routing Problems can be roughly divided into *Route Construction Heuristic (based on savings algorithm, the sweeping algorithm and the nearest neighbour algorithm)* and *Solution Improvement Heuristics (applying all kind of* neighbourhood operators) (Bräysy & Gendreau, 2005a).

In our study heuristic algorithms are used to reach a satisfying solution. The main reason for this is the fact that currently the logistics service provider in question is applying the Shortrec (Ortec) software for the daily route planning. Applying the same program in our research makes comparision of the calculations more realistic. The Shortrec software uses the sequential insertion algorithm followed by a variety of improvement operators (Bräysy & Gendreau, 2005) to improve initial solutions. Here it should be mentioned that the literature of solution algorithms shows some ambivalence. Poot et al. (2002) conclude that the savings algorithm outperforms the insertion algorithm. However, they state also that the performance of the algorithms largely depends on the type of scenario being used. On the other hand Kant et al. (2008) choose the sequential insertion algorithm over the savings algorithm. Furthermore, Liu & Shen (1999) applied the sequential insertion algorithm to the particular case of the FSMVRPTW successfully. Based on these research experiences (Liu & Shen, 1999; Kant et al., 2008) we applied the sequential insertion heuristic.

3. Case Study: Amsterdam

In this section the model will be applied for a real case in the innercity of Amsterdam. First we introduce the current policymaking with respect to urban freight delivery in the

[1] In reality the operation range also depends on the driving behaviour of the driver, the inclination of the infrastructure and the environment. Quantifying these effects on the operation limit was beyond the scope of this research.

innercity of Amsterdam. After that we explain the technical details of an electric vehicle (the Cargohopper) followed by a short elaboration of the intended logistical process.

Freight policy: urban freight action plan

The Municipality of Amsterdam developed an action program freight transport (Dutch: '*Actieplan Goederenvervoer'*) in 2007 (DIVV, 2008). The main reason for the development of the program has been the insufficient air quality of Amsterdam. The goal of the program was to organise urban freight traffic (> 3.5 tonnes) in such a way that this sector could contribute to the improvement of the air quality of Amsterdam, without the hindrance of a well-functioning urban economy (DIVV, 2008). Besides the Action program for freight transport, the Municipality of Amsterdam in 2009 developed a program for stimulating the usage of electric transport in the city (DIVV, 2010). This program was mainly created to meet the standards for air quality in 2015. The concentrations of particulate matter (PM_{10}) in Amsterdam are not problematic, but on most traffic bottlenecks the concentration of nitrogen dioxide (NO_2) is too high (TNO, 2009). The Municipality of Amsterdam has therefore formulated the ambition to have 10,000 electric vehicles in use in the city by 2015, and that all transport would be driven electrically in 2040. Electric vehicles have significantly lower operational costs than diesel vehicles (see Table 1).

Table 1: Fuel costs for electric and non-electric (Diesel) vehicles (DIVV, 20010).

	Electricity	*Diesel*
Usage (per 1,000 km)	225.33 kWh	200 litres
Costs per unit	€0.31/kWh	€1.0769/litre
Costs per 1,000 km	€69.85	€215.38

Although electricity is much cheaper than diesel, the purchase costs of batteries and vehicles themselves is higher. The Municipality of Amsterdam therefore stimulates the acquisition of electric vehicles by providing subidies. Despite these subsidies, the pressure on operations remains higher than with conventional vehicles.

Electric vehicles

For the implementation of the electric vehicles in Amsterdam two types are taken into consideration: the Cargohopper Type 2.1 and the Cargohopper Type 2.2 (see Figure 1).

Figure 1: Cargohopper Type 2 (www1, 2012)

The Cargohopper Type 2 is able to transport both packages and pallets and the top speed of Type 2 is approximately 55 km/h. The tractor is a customised Alkè XT, which is an electric multipurpose vehicle. The trailer is designed in a way such that two Euro-pallets can fit next to each other and is high enough to fit roll-containers. The dimensions on the inside of the trailer are 1.68 x 6.40 x 1.90 meter. The outside width of the trailer is 1.75 meter. The Cargohopper Type 2 has a maximum capacity of 10 euro-pallets or 16 roll-containers. Next to that it is estimated that approximately 500 packages can fit into the trailer. This Cargohopper type is equipped with pure lead batteries of 26 kWh. Recent tests show that the operation range of the Cargohopper Type 2 is approximately 100 kilometres. The solar panels on the roof of the trailer will only add to the maximum range of the vehicle (Alkè, 2011). The energy contribution of the solar panels are unknown yet in pratice and therefore omitted in this research. The limited operation range provides a challenge to implement of the Cargohopper for the delivery processes in Amsterdam. The Cargohopper Type 2 can also be purchased with an additional exchange battery that can be changed at the depot. The properties of both vehicle types are shown in Table 1.

Table 1: Vehicle properties Cargohopper Type 2.1/2.2 (de Heus, 2012)

Description	*Cargohopper Type 2.1*	*Cargohopper Type 2.2*
Vehicle type (k)	1	2
Purchase costs [€]	**87,920**	**97,195**
$\boldsymbol{f_k}$ [€/day]	**107.94**	**118.32**
$\boldsymbol{q_k}$ (pallets)	10	10
$\boldsymbol{q_k}$ (packages)	500	500
$\boldsymbol{q_k}$ (kilogram)	2750	2750
$\boldsymbol{D_k}$/day [km]	**100**	**200**
$\boldsymbol{D_k}$/battery [km]	100	100
Operational speed [km/h]	50	50

In the Table 1 the purchase costs and fixed costs (f_k) are represented. The differences in costs are only caused by the purchase costs of the exchange battery. Basically, the batteries of the Cargohopper should be able to provide for an operation range (D_k) of 150 kilometre (Alkè, 2011). However, the environmental temperature and the inclination of the routes have strong influences on the performance of the battery. First practical test with the Cargohopper Type 2.1 in Utrecht turned out that the operation range is approximately 100 kilometres per battery. In our case study it is assumed that Cargohopper type 2.1 can drive 100 kilometres per day and Cargohopper type 2.2. in theory can drive 200 kilometres per day, with a maximum of 100 kilometres per trip. Special attention should be paid to the moment of changing the battery.

Given these vehicle types the following fleet compositions (FC) are configured in the modelling experiments (see Table 2).

Table 2 - Fleet Compositions (FC) (de Heus, 2012)

	Cargohopper				*Cargohopper*		
FC	*2.1*	*2.2*	*Total*	*FC*	*1*	*2*	*Total*
1	3	0	3	**6**	0	4	4
2	0	3	3	**7**	2	2	4
3	1	2	3	**8**	3	1	4
4	2	1	3	**9**	1	3	4
5	4	0	4	**10**	5	0	5

Logistical situation

The city centre of Amsterdam is an environmental zone with access restrictions. Only trucks with Euro 4 and 5 are allowed to enter. Currently the logistics service provider is distributing cargo in this environmental zone straight from their depot in Almere. In order to reach Amsterdam the vehicles from the Almere depot have to drive approximately 20 kilometres over the A10 motorway. Due to the limited operation range of the electric vehicles a potential transhipment hub has to be used. Figure 2 shows a schematic representation of the intended process. The dots represent the depot in Almere as well as a potential transhipment hub. The thick line represents the trip between the depot and the transhipment hub with conventional vehicles. The other lines represent the routes from the transhipment hub by the Cargohoppers. Both operations are carried out by the same logistics service provider.

Figure 2: Distribution of goods form Almere depot to transhipment hub to the inner city of Amsterdam shown in Shortrec (de Heus, 2012)

In Figure 3 the routes of the vehicles that carry out the distribution to the orders outside the environmental area of Amsterdam are left out. The cargo composition of the Almere depot to the customers in the environmental zone is presented in Table 3.

Table 3: Cargo composition within the environmental zone Amsterdam (for a representative week)(de Heus, 2012).

	Number of Customers	*Pallets*	*∑ weight pallets [kg]*	*Packages*	*∑ weight packages[kg]*	*Total weight [kg]*
Monday	155	24	7,133	434	3,226	10,359
Tuesday	201	33	5,489	590	4,422	9,911
Wednesday	196	33	5,587	579	4,761	10,348
Thursday	219	37	9,139	669	5,009	14,148
Friday	215	38	8,717	996	5,307	14,024
SUM	986	165	36,065	3,268	22,725	58,790

The solution space of the problem is determined using the primary performance indicators average costs per delivery (constraint *1B*) and average service level (constraint *2*). For each of these performance indicators boundary values were defined to be reached by any fleet composition in order to be successful. Table 4 shows the performance of the Fleet Compositions 1 to 10 in the basic scenario.

Table 4: Fleet compositions results basic scenario

Fleet Composition	*Vehicle Type*		*Average Service level*	*Average*[(1)] *Costs*
	1	*2*	*/week*	*/delivery*
1	3	0	88.4%	70.9%
2	0	3	90.3%	72,5%
3	1	2	87.1%	74.8%
4	2	1	88.1%	74.5%
5	**4**	**0**	**99.3%**	**73.4%**
6	0	4	99.9%	75.9%
7	2	2	99.6%	74.9%
8	3	1	99.3%	74.6%
9	1	3	99.8%	82.0%
10	5	0	100.0%	90.7%

(1) Percentage of the average revenues

The first four fleet compositions have an average service level below the 99% threshold. Therefore these fleet composition fall outside the solution space and are disregarded for further analysis. The fleet composition with the lowest average costs per delivery is advised to start implementation. This fleet composition (5) consists of four vehicles of vehicle Type 2.1.

4. Scenarios & evaluation

The six remaining fleet compositions are subjected to a variety of scenarios, in order to test robustness of the fleets. Scenario 1, the base case, has a cargo composition for a representative week. The operation range is set to 75 kilometres for vehicle type 2.1 and 150 kilometre for vehicle type 2.2. Both ranges are less compared to the specifications of the supplier to introduce some safety range to compensate for different driving behaviours. The operational speed is not reduced. The remaining scenarios are all reconfigurations of Scenario 1. In each separate scenario a different variable is altered. These scenarios are summarized in Table 5. Scenario 4 and 5 are different compared to the first (1, 2 & 3) scenarios. In Scenario 4 the safety margin on the operational range is left out. This scenario evaluates the fleet compositions with an extended operational range of 100 kilometres for vehicle type 2.1 and, with exchange batteries, an extended range of 200 kilometres for vehicle type 2.2. Scenario 5 is developed in case the Cargohopper drives with a lower average speed (75%), caused by for instance congestion in the city centre or bad weather conditions.

Table 5: Scenarios

Scenario	*Cargo Composition*	*Operational range (km)*	*Operational Speed (km/hour)*
1 – Base case	Reference Week	75/150	50
2 – Busy week Friday	5 * Friday Reference Week	75/150	50
3 – Quiet week	5 * Monday Reference Week	75/150	50
4 – Increased range	Reference Week	100/200	50
5 – Low speed	Reference Week	75/150	37.5

Table 6: Cost comparison

Scenario	***Cost current delivery***[(2)]	*Cost outside Centre*[(3)]	*Cost for delivery to UCC*[(3)]	*Cost Delivery from UCC*[(3)]	*UCC operating Cost*[(3)]	***Total cost***[(2)]
1	**100%**	71.6%	2.8%	21.3%	4.3%	**110.0%**
2	**105.3%**	70.3%	3.4%	22.2%	4.1%	**115.8%**
3	**77.5%**	68.5%	3.4%	22.6%	5.5%	**86.9%**
4	**100%**	71.3%	2.8%	21.6%%	4.3%	**110.4%**
5	**100%**	70,9%	2.8%	22,0%	4.3%	**111.1%**

(2) All cost are compared to the current cost of delivery in the basic scenario (= 100%)
(3) All specified cost are compared to the total cost of the specific scenario (=100%)

As noted in Table 6 all scenarios result in higher cost than the current method of delivery. This is in line with the findings in other city distribution studies (Browne et al., 2005; van Duin et al.,2010) where financial feasibility is hard to be obtained without any subsidy. Based on NPV-calculations with an annual inflation rate of 2.4% and 8% discount rate, initial investment of €351,680 (4 Cargohoppers Type 2.1), total salvage value of the vehicles of €9,704 (after 4 years), considering all the cost (see Table 4 + insurance costs (€11,600)), and annual revenues (estimated by multiplying the average revenue per delivery by the total customers served in the inner city of Amsterdam) we found two positive NPVs for scenario 1 and 4 (de Heus, 2012). In additional to these results, it should be mentioned that the Municipality might be willing to provide an allowance for the so called 'non-profitable top' which refunds 50% of the additional purchase costs of the electrical vehicles over the costs of a regular vehicle. This positively effects the NPVs in all scenarios.

The UCC operating cost are not part of the model. The surface of the location is approximately 440 m^2. The rental costs are expected to be €130 per m^2, which can be shared with another company. Including the costs for parking spots and other facilities, the costs of the UCC location are estimated to be at maximum €50,000 per year, including service costs at maximum €57,500 per year.

CO_2 emission reduction

For the basic scenario the total travelled distances are compared for the current way of distributing with combustion engines and distributing with electric vehicles. Both scenarios are presented in Table 7.

Table 7: Weekly kilometres travelled by vehicles with combustion engines (current situation), and combustion vehicles and electric vehicles (scenario 1).

Day	*Current situation*	*Scenario 1*	*Difference*
Monday	1.852	1.521	331
Tuesday	2.090	1.740	350
Wednesday	2.522	2.000	522
Thursday	2.294	1.928	367
Friday	2.173	1.787	386
Total	**10.931**	**8.975**	**1.956**

Table 7 shows mainly the difference in the travelled kilometres by regular vehicles and electric vehicles. Since the comparison is made for the whole serving area of the Almere depot, it is unknown what the effects on the routes of the vehicles delivering outside the environmental zone are. Therefore, Table 7 only gives an indication. However, the result of 19% reduction of the total distance travelled are in line with the findings of Browne et al. (2011) where the total distance travelled the CO_2eq emissions per parcel delivered as a result of this delivery system fell by 20%. Extrapolating this to a year as an estimation yields an annual reduction of vehicle kilometres of 101.712 kilometres. Assuming a fuel consumption of a litre of diesel every five kilometre the annual reduction in diesel consumption results in a reduction of 20.342 litres diesel. The reduction of direct emission as result of burning a litre of diesel is 2,63 kilogram per litre. The indirect reduction yields to an indirect reduction of 0,428 kilogram per litre (Bhatia & Ranganathan, 2004). Hence the reduction of CO_2 emission is calculated by multiplying 20.342 litres of diesel a year with 3,058 kilogram per litre, a yearly reduction of 62,207 kilograms a year.

However, the electricity consumed by the electrical vehicles also adds to the CO_2 emission. In this research the emission resulting from the consumption of a kWh of energy is set to 0.332 kilogram (Energie Nederland & Netbeheer Nederland, 2011) and an energy consumption of 0.35 kWh per kilometre. In the basic scenario each Cargohopper drives 14.438 kilometres leading to an energy consumption of 5.005 kWh. The whole fleet of four Cargohoppers consume 20.020 kWh a year. The indirect emission that is caused by operation is 6.647 kilogram a year. The annual net reduction in CO_2 emission is 55.560 kilogram. This leads to a 90% reduction in CO2-emissions which is also comparable with the findings of Browne et al. (2011) where their trial system was able to virtually eliminate CO_2 emissions per parcel delivered in the City of London. In our study we added the electric energy consumption and related CO_2-emissions. This is different from the assumptions made in the study of Browne et al. (2011), where they assume that the operation of these vehicles does not result in any fossil fuel consumption or greenhouse gas emissions, as the electricity they used was produced from renewable sources. It should be kept in mind, therefore, that the reduction will be more than 90%, due to the potential energy contribution of renewable resources. Additional calculations were made for conventional vehicles (i.e. assuming identical loading capacity, 4 diesel vans driving 14438 kilometers in the basic scenario) using the new hub lead to a reduction of 36% reduction in CO_2-emissions. However, this is not a reliable estimation since current delivery operations are executed with busses, (small) lorries and city trailers with different costs and energy consumptions. Route optimisation for these operations was not calculated in this study.

5. Conclusions

Like Davis and Figliozzi (2013) our contribution includes the evaluation of a wide range of scenarios, to allow a better understanding of the impact of routing constraints, electric vehicle characteristics and traffic/driving environment on the cost differences between electric and conventional commercial vehicles. In addition, we introduce the relaxation of the usual demand constraints into a minimal service constraint. The mathematical formulation of FSMVRPTW by Bräysy et al. (2008) is adjusted for electric vehicles. Our application shows that electric trucks will become competitive when the cost savings from the reduced operational cost are sufficient to overcome the higher initial purchase costs. In our NPV-calculations we find that two scenarios have a positive value after four years. In these scenarios the (high) load factor was the principle factor to obtain a positive NPV; this is more critical compared to diesel trucks since the electric vehicles have far smaller load limits in both weight and volume. Based on two scenarios with a positive NPV, and the potential acquisition of subsidies from the Municipality of Amsterdam for electric vehicles, implementation of the system appears feasible. Like the trial in London, which proved successful from the office supplies companies perspective in both environmental and economic terms (Browne et al., 2011), our ex-ante study is positive.

Due to our study both the municipality and the logistic service provider know exactly how many vehicles of what type need to be acquired. For the municipality, this helps to assess the level of subsidies they need to provide in order to obtain a free CO_2-zone in the inner city. The logistics service provider obtains a detailed insight in its investment costs, running costs and services levels of the delivery by the electronic vehicles. Based on the results from this study, the logistics service provider decided to buy 4 Cargohopper (2.1) vehicles.

Based on our research findings in Amsterdam we conclude that the current generation of electric vehicles, as a part of a broader urban consolidation concept, has the ability to perform urban freight transport efficiently (19% reduction in vehicle kilometres) and meanwhile has the capability to improve air quality in the city centre due to the use of electric vehicles as well as reduce the CO_2-emissions for making the same deliveries and pick ups in Amsterdam by 90%, and reduce noise nuisance in the inner cities of our (future) towns.

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