EL FORT

ELectric Fleet Optimization in Real-Time

Public Report

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Project in FFI Efficient and Connected Transport Systems

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Kort om FFI

FFI är ett samarbete mellan staten och fordonsindustrin om att gemensamt finansiera forsknings- och innovationsaktviteter med fokus på områdena Klimat & Miljö samt Trafiksäkerhet. Satsningen innebär verksamhet för ca 1 miljard kr per år varav de offentliga medlen utgör drygt 400 Mkr.

För närvarande finns fem delprogram; Energi & Miljö, Trafiksäkerhet och automatiserade fordon, Elektronik, mjukvara och kommunikation, Hållbar produktion och Effektiva och uppkopplade transportsystem. Läs mer på www.vinnova.se/ffi.

1 Sammanfattning

Projektet har forskat på och utvecklat en ny algoritm för att prediktera energiåtgången för elektriska distributionslastbilar i stadsmiljö där hänsyn tas till en rad nya parametrar. Den största begränsningen för elektriska fordon generellt är givetvis batterikapaciteten som bestämmer den längsta sträcka som kan köras på en uppladdning. Den påverkas av flera yttre faktorer såsom antalet accelerationsförändringar (t. ex. antalet stopp pga korsningar), topografi (t. ex. backar) och den omgivande trafiken. Vidare, så beror energiförbrukningen också på last, motoreffekten, kupévärmaren (kyla respektive värme) och kör mönster.
Den utvecklade algoritmen heter ”Two-Stage Electric Vehicle Routing Problem (2sEVRP)” och är baserad på den välkända ”Vehicle Routing Problem (VRP)” introducerad redan på 50-talet. 2sEVRP predikterar energiåtgången för ett elektriskt fordon i stadsmiljö där hänsyn tas till topografi, hastighet, motoreffektivitet samt effekten av inbromsningar och acceleration. Algoritmen har visat att numeriska resultat överensstämmer bra med högupplösta fordonssimuleringar i stadsmiljö. 2sEVRP är en viktig delkomponent för att kunna prediktera och ruttoptimera en hel flotta av elektriska distributionslastbilar i stadsmiljö.
Projektet har finansierat en doktorand till licentiatexamen. Det har resulterat i en konferenspublikation, en journalpublikation samt en licentiatuppsats. Vidare, så har även ett mastersarbete utförts inom ramen för projektet.

2 Executive summary in English

The project has researched and developed a new algorithm to predict energy consumption for electric distribution trucks in the urban environment, taking into account a number of new parameters. The biggest limitation for electric vehicles in general is of course the battery capacity that determines the longest distance that can be driven on a single charge. It is influenced by several external factors such as acceleration (e.g., the number of stops due to crossings), topography (e.g. hills) and the surrounding traffic. Furthermore, energy consumption also depends on payload, engine efficiency, auxiliaries (cooling and heat) and driving patterns.
The developed algorithm is called "Two-Stage Electric Vehicle Routing Problems (2sEVRP)" and is based on the well-known "Vehicle Routing Problem (VRP)" introduced in the 50's. 2sEVRP predicts the energy consumption of an electric vehicle in urban environments, taking into account topography, speed, engine efficiency, and the impact of braking and acceleration. The algorithm has shown that numerical results are consistent with high resolution vehicle simulation in urban environments. 2sEVRP is an important component to be able to predict and route optimize a whole fleet of electric distribution trucks in the urban environment.
The project has funded a PhD student for a licentiate degree. It has resulted in a conference publication, a journal publication and a licentiate dissertation. Furthermore, a master's thesis has also been carried out within the framework of the project.

3 Background

During the recent past the world has become more urbanized, with this trend set to continue at least in the near future. Over half of the world's population live in cities and by 2050 the proportion can reach over 70%, according to projections by the United Nations. With this trend the concept of smart cities is seen as a key to make the transition while improving the overall liveability in urban environments. One of the pillars of that concept is smart mobility, both for people and goods. As cities grow and become denser, the challenge of efficient transport also grows. Several associated issues emerge, such as use of public space, pollution levels, noise, road congestion and safety.

Goods transportation is an essential part of the economy. With increased urbanization and the event of e-commerce, urban freight volumes are on the rise. This means that many more commercial vehicles will be needed and that already existing problems will potentially increase. Additionally, customers are requiring faster and more flexible last-mile deliveries as well as the ability to follow up their packets on-line. All of these put high pressure on logistics systems, especially when it comes to planning and scheduling.

Commercial vehicles, which typically use diesel engines, generate high emissions. From nitrogen oxide (NOx), particulate matter to carbon dioxide (CO_2), these vehicles are a significant contributor to pollution due to higher utilization and higher fuel consumption than personal vehicles. A direct consequence is that, according to the World Health Organization, millions of premature deaths are estimated due to air pollution in addition to the problem of climate change. Furthermore, their share on congestion and noise increases the spectrum of the problem.

On the other hand, much has been talked about the three main transformations in transportation:

- Electrification: exchanging internal combustion engines for electric powertrains can reduce vehicle energy use and emissions.
- Automation: from assisted driving to driverless vehicles, this technology has the potential to increase safety, reduce labour costs, enable cheaper travel and more productive use of time.
- Connectivity: is an enabler for shared mobility and can contribute significantly to increased vehicle usage and uptime, more and better traffic information, faster and cheaper logistics.

These three revolutions have even greater potential when combined. Electric, connected, automated vehicles can enable a much better vehicle utilization, and consequently impact positively in all the problems discussed above: use of public space, pollution levels, noise, road congestion and safety. Together with de-carbonization of electricity production, vehicle electrification is the strongest response to reducing pollution.

One of the most interesting usages of electric vehicles in urban logistics is night deliveries. Since these vehicles are much quieter than vehicles with combustion engines, they make it feasible to drive even in residential areas at night and early morning. As a consequence, there is potential to reduce congestion, improve punctuality, save time and costs.

There are several regions and cities developing plans for reducing transport emissions. Over 200 cities currently have emission and access regulation zones. Some major cities, such as Madrid, Paris and Mexico City, are announcing diesel bans, while the UK and France have recently announced future sales bans on fossil-fuel vehicles. Additionally, several countries such as Norway are releasing ambitious vehicle electrification targets. In response to that, many vehicle manufacturers have been disclosing plans for electric models and even transport companies like DHL have looked into developing their own electric vehicles.

Current electric vehicles still have limitations despite the latest technology developments. They are mostly associated with batteries which are still big, heavy and costly. Because of that, most vehicles have limited driving range and a high purchase cost. Additionally, charging takes a relatively long time and charging infrastructure is scarcely available. On the positive side, their total cost of ownership (TCO) is already on par with their diesel counterparts for some applications or is projected to be on par in the coming years. Continued improvement in battery cost and density together with high demand from customers can potentially decrease vehicle cost and rapidly increase sales. Furthermore, in terms of power demand, adoption of electric trucks is expected to increase global electricity consumption by only around 3% by 2050, including heavy-duty trucks.

Due to the range limitation, planning of driving routes for electric commercial vehicles becomes paramount to avoid them running out of battery. Since diesel vehicles typically have a much longer driving range, planning tools are not mandatory. Although the profit margin for transport companies is usually low and fuel is one of the main costs, many of them use simple logistics schemes and rely on driver experience for planning the daily routes. It is not uncommon to have packets separated by postcode and the drivers themselves planning their routes prior to departure. But for electric trucks there is a strong potential and need for route planning tools to deal with the limited driving ranges.

This project focused on the development of energy estimation and routing algorithms for electric commercial vehicles. The main target is battery electric medium-duty trucks used for urban distribution of goods. The methods developed can be extended and integrated into real world tools for logistics companies. The implemented systems can generate the following potential benefits:

- Enable the use of electric vehicles and all its associated benefits, helping to reduce local pollution and making feasible other logistics possibilities such as night delivery.
- Improve fleet utilization by better planning the routes and schedules for the vehicles, potentially lowering operational costs and increasing profitability for the transport companies.
- Increase delivery punctuality by using traffic data in the route planning and making it possible to develop additional services such as customer notification when the vehicle approaches.
- Be able to react faster when unpredictable situations occur such as traffic accidents or unexpected congestion, allowing for dynamic prediction of energy consumption and real-time adjustments of transport plan including recharging when necessary.
- Tailor the fleet size and mix, choosing vehicles with correctly specified battery capacity for the expected assignments, taking into account total cost of ownership for the transport company.
- Support charger station planning by simulating different scenarios with battery capacity and charger location.
- Be part of the complete automated logistics system, when automated driving is integrated with automated planning and other activities such as automated loading and unloading.

4 Purpose, research questions and method

The main purpose of this project was to develop a method to plan routes that minimize energy consumption of Electric Commercial Vehicles (ECV) for urban distribution of goods, making sure that their battery capacities are enough to drive the complete routes. In order to do that it is necessary to precisely estimate energy consumption while planning the routes. Charging stops should be planned whenever needed. The basic problem is derived from the Vehicle Routing Problem (VRP).

The main research questions investigated are:
1. Which parameters (e.g. topography, speed) have the largest impact in energy consumption of ECVs?
2. How do these parameters influence the choice of energy optimal routes?
3. How to incorporate these parameters to enhance route planning for ECVs?
4. What is the influence of paths between nodes in energy consumption estimation?
5. What are the benefits (e.g. energy savings, charge planning) of integrating a more accurate energy consumption model into VRPs?

Some of the typical parameters considered in the VRP literature for estimating energy consumption are weight, topography and speed (usually average). However, several other parameters are typically not considered, such as auxiliaries, more precise powertrain efficiency and detailed speed profiles (e.g. time-dependent congestion, acceleration and braking). But above all, what previous VRP formulations do not include is the influence of the paths between pairs of nodes to be visited (e.g. customers). Since most VRPs target distance or travel time minimization, the details of the paths are not so relevant. But for energy estimation, detailed topography and speed profiles are paramount to estimate energy consumption accurately.

There was a significant effort to verify the methods being developed using relevant scenarios. Therefore the road network from Gothenburg was used for the test cases. For the energy estimation, a high-fidelity vehicle model, the Volvo Global Simulation Platform, was used as benchmark and the results from the developed models were compared with precise simulations.

5 Objectives

The initial goal was to develop a dynamic fleet routing method combining real-time vehicle status, fleet and traffic information (both local and global) to increase efficiency of goods distribution. The aim was to provide a novel route decision approach to real-time optimize a complete fleet of electric trucks for urban distribution of goods.

During the project it was noticed that existing energy consumption estimation methods used for routing were very imprecise, making it impossible to accurately plan the routes and make sure that they were feasible with respect to battery capacity and energy demand. Therefore the project focused on that part, since it is a foundation to be used in electric vehicle routing. The 2sEVRP model was then developed, incorporating a precise estimation method into the routing model.

6 Results and objectives fulfillment

The two papers written are both focusing on routing problems for electric commercial vehicles. They look into the different factors that affect routing and energy consumption for urban distribution of goods. The foundation of the papers is the Vehicle Routing Problem, which has been extended in different ways in the two papers. Additionally, the two papers incorporate energy consumption estimation models into the VRP, in order to minimize energy consumption while routing. Battery capacity is considered and charging is planned when the battery is not enough to complete the route. Other constraints are payload capacity and time-windows, which are typically included in VRP formulations. None of the papers focus on solution methods, which is a very common topic especially in the field of computer science. Since the VRP is a difficult combinatorial optimization problem, to find optimal solutions is not an easy task. But instead, the focus has been on numerical experiments to show the properties of the proposed formulations and analyse the precision of the described methods.

7 Dissemination and publications

7.1 Knowledge and result dissemination

How have the project results been used and disseminated?	Mark X	Comments
Increase knowledge in a specific area	X	The body of knowledge in electric vehicle has been increased with two papers
Be passed on to other advanced technological development projects	X	Results are being carried over to other projects by the partners
Be passed on to product development projects		
Introduced to the market		
Used in investigations, regulations, permit matters/political decisions.		

7.2 Publications

Paper 1

Basso, R., Lindroth, P., Kulcsár, B., Egardt, B., Traffic aware electric vehicle routing. 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC). IEEE, 2016. p. 416-421.

This paper's main motivation is to look into the effect of different factors in routing electric vehicles. Besides total vehicle weight and topography, there is a special focus on speed. The paper puts together different elements described in the previous chapters and formulates a VRP model that includes time-dependent speed and an energy consumption model similar to the Pollution Routing Problem. The idea is to be able to capture speed fluctuations in the road network at different times during the day and analyze the impact in energy consumption and routing for electric vehicles. Differently from the PRP, the model assumes that the vehicle should follow the traffic flow, so the speed is not a decision variable. Furthermore, the formulation is a mixed-integer piecewise linear problem, which makes it easier to solve than alternative nonlinear formulations such as \cite{Goeke15}. The model also includes a weighted cost function that minimizes energy consumption and total travel time for the route, since the latter is usually an important parameter for the transport companies. One of the most interesting results from the numerical experiments is that when different factors such as topography and speed have high variability, the impact in energy consumption is more significant. Therefore it is important to include all those parameters when routing electric vehicles.

Paper 2

Basso, R., Kulcsár, B., Egardt, B., Lindroth, P., Sanchez-Diaz, I., Two-stage Electric Vehicle Routing Problem - Energy estimation and path finding integrated with routing, to be published.

In this paper the Two-stage Electric Vehicle Routing Problem (2sEVRP) is presented, with a special focus on energy consumption estimation integrated with routing. The method has two stages, first finding the best paths between all customer nodes, charging stations and depot, then finding the best route including battery and time-window constraints. To the best of our knowledge no published paper has taken into account the paths when estimating energy consumption, resulting in significantly inaccurate energy and time estimation. As a result, when the existing methods are used for routing electric vehicles, there is a serious risk that their battery capacity will not be enough to complete the planned routes.

The proposed energy consumption estimation model takes into account detailed information about topography, speed and the effect of acceleration and braking at traffic lights and intersections. The method calculates energy consumption parameters associated with each road link in the network. These parameters can be easily aggregated for the paths and for the complete route, making it possible to easily estimate energy consumption. Additionally, the powertrain efficiency is considered as a function, which further increases the prediction accuracy. The presented model targets energy minimization in the cost function and takes into account payload and auxiliary systems. Since auxiliary consumption is considered linear with time, the model takes into account time minimization indirectly in the cost function.

Numerical experiments were performed with the road network from Gothenburg-Sweden and high-fidelity vehicle model simulations. The focus was medium-duty battery electric trucks for urban distribution of goods. The results show high accuracy in terms of time and energy consumption estimation when compared with simulations. It was also demonstrated that routing for electric vehicles is highly dependent on good energy estimations, especially when battery capacity is limited and it is necessary to plan charging. Existing methods were shown to be unreliable for that application. Furthermore, by being able to precisely estimate energy consumption, it was possible to generate less energy demanding routes.

8 Conclusions and future work

Electric Commercial Vehicles are currently gaining momentum and there are several manufacturers that released plans for rolling out new models in the coming years, apart from the already existing ones. There is also a strong pull from transport companies mainly driven by the end-customers' interest in green transportation but also by the signals from authorities towards regulations in cities. On the other hand there are still challenges and limitations with the technology to be able to deploy these vehicles in current logistics operations. Despite latest advancements and optimistic future projections, one of the main issues is still battery capacity, affecting range, charging time and payload of trucks. Considering that heavier and heavier vehicles will be electrified over time, this issue will continue to exist in the coming years. Therefore it is important to tackle the problem with smart tools to support adoption of ECVs in current logistic operations.

The papers presented in this thesis focus on energy consumption estimation and route planning for urban distribution of goods with ECVs. They show different perspectives of routing and the factors that affect energy consumption for electric trucks.

Paper 1 is mostly seen as a step towards Paper 2. It proposes a time-dependent electric vehicle routing problem with a relatively simple energy estimation model. Numerical experiments show how different aspects such as road topography, speed and weight affect the routing results.

Paper 2 introduces the 2sEVRP, a two-stage routing method with an accurate energy consumption estimation. With that method it is possible to calculate cost parameters associated with the road network, capturing important factors that affect energy consumption. Inclination, speed, acceleration and braking at traffic lights and intersections, as well as auxiliary systems and powertrain efficiency in traction and regeneration modes are embedded in the cost parameters. They can be easily aggregated in the two stages of the method in order to find the best route and estimate energy consumption and travel time.

In the numerical experiments it was shown that the estimations deviate only 1.54% in average when comparing with high fidelity vehicle simulations for 20 test instances. It was also shown that savings of up to 7.76% can be achieved when compared with traditional distance minimizing routing. Moreover the method was shown to be much more reliable when planning charging for electric vehicles when compared with existing models.

Future work

Despite the clear advances, there are several simplifications used in the models presented in the two included papers. Related to charging, both papers consider linear charging time, which does not reflect reality, where charging gets slower after the battery reaches about 80\% State of Charge. The models also assume that the battery is always fully charged when leaving the terminal and after visiting charging stations, but it could be interesting to be able to recharge only partially and save time. Additionally, battery lifetime is affected by how often and how much the battery is charged and used, therefore future models should take that into account when planning charging stops.

None of the papers focused on solution methods for the problems formulated. The problem can get particularly demanding for larger instances with multiple vehicles, many customers and several charging stations. For that reason efficient solution algorithms are important to be able to use the models for real scenarios.

Since the energy estimation precision was evaluated comparing with simulations, it would be very interesting to compare estimated energy and time with actual data from real vehicles driving the planned routes. Furthermore the 2sEVRP could be tested for different kinds of vehicles and different cities. Historical speed data could be used as input for the models.

Stochastic parameters

Although the 2sEVRP method includes many realistic aspects and it was shown to be precise when comparing with simulations, there are several input parameters that can be difficult to predict when driving with vehicles in real traffic scenarios. The approximations used in the model will never reflect exactly the reality. Input parameters such as topography and the powertrain efficiency function do not have the granularity necessary to depict all the details of road inclination and powertrain operation. But above all, driving behaviour and traffic flow should be considered random since they can vary considerably. They can greatly affect speed, acceleration, braking and stops, consequently affecting energy consumption. Since the two papers presented deterministic models, one of the most important future research topics is to take a stochastic approach to energy estimation and routing.

9 Project participants

Participant	**Role and area of responsibility**	**Personnel and other resources**
Volvo GTT	Project leader	Katrin Sjöberg
Volvo GTT	PhD student	Rafael Basso
Volvo GTT	Engineer	Peter Lindroth
Chalmers – Electrical Engineering	PhD supervisor	Balazs Kulcsar
Chalmers – Electrical Engineering	PhD co-supervisor	Bo Egardt
Chalmers – Technology Management and Economics	PhD co-supervisor	Ivan Sanchez-Diaz
Chalmers – Technology Management and Economics	PhD co-supervisor	Per-Olof Arnäs