EL FORT 2

ELectric Fleet Optimization in Real-Time (phase2)

Public Report

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Project in FFI Efficient and Connected Transport Systems

Contents

1 Sammanfattning

Projektet har forskat kring och utvecklat nya metoder för att prediktera energiförbrukning och planera rutter för elektriska distributionsbilar som används i stadslogistik. Den viktigaste begränsningen för elfordon är deras batterikapacitet, som avgör deras räckvidd. Sträckan som kan köras med en laddning beror på flera externa faktorer som acceleration (t.ex. antalet stopp på grund av korsningar), topografi (t.ex. backar) och den omgivande trafiken. Dessutom beror energiförbrukningen på lastvikt, drivlinans verkningsgrad och förarbeteende.
Projektet levererade två tidskriftsartiklar, en publicerad och den andra under granskning, samt en doktorsavhandling. Artiklarna tar hänsyn till olika aspekter av problemet av ruttplanering för kommersiella elektriska fordon, inklusive prediktering av energiförbrukning. Huvudstrategin är användningen av maskininlärning för att ta hänsyn till stokasticitet och dynamik i transportverksamheten. Resultaten har validerats med hjälp av fordonsmodeller med hög kvalitet, realistiska trafiksimuleringar och data som samlats in från verkliga fordon som kör i Göteborg.
Projektet har sponsrat en doktorand för att nå doktorsexamen. Det har resulterat i konferenspresentationer, två tidskriftsartiklar och en doktorsavhandling. Dessutom har en magisteruppsats genomförts inom ramen för projektet.

2 Executive summary in English

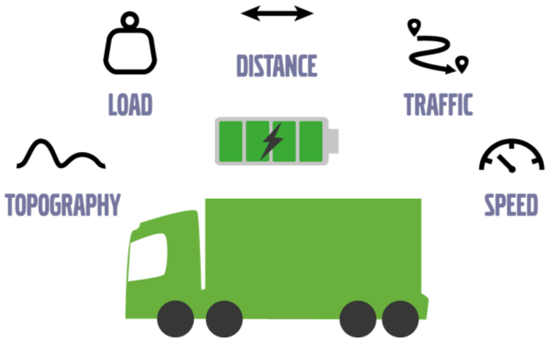
The project has researched and developed new methods to predict energy consumption and plan routes for electric distribution trucks used in urban logistics. The most important limitation of electric vehicles is their battery capacity that determines the distance that can be driven on a single charge. 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 and driving behavior.
The project delivered two journal papers, one published and the second under review, as well as a PhD thesis. The papers consider different aspects of the problem of routing electric commercial vehicles including energy consumption prediction. The main approach is the use of machine learning to take into account stochasticity and dynamism in transport operations. The results have been validated using high fidelity vehicle simulation models, realistic traffic simulation and data collected from real vehicles driving in Gothenburg.
The project has funded a PhD student to reach it doctor degree. It has resulted in conference presentations, two journal articles and a doctoral dissertation. Furthermore, a master's thesis has also been carried out within the framework of the project.

3 Background

During recent years, there has been a growing effort to promote sustainable fuel solutions, with special focus on increasing the use of electric vehicles. But currently there are still limitations despite the latest technology developments and the positive trends. The constraints 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. Due to the range limitation, proper planning of driving routes for electric commercial vehicles becomes paramount to avoid battery depletion while driving. Therefore, there is a strong potential and need for route planning and range prediction tools for electric trucks.

As Volvo strengthens the focus on electromobility, all the challenges in delivering electric transport solutions become very relevant. Since the battery cost represents more than one third of the total cost of the vehicle, it becomes imperative to maximize the use of the vehicle with respect to energy consumption and battery capacity. It is essential to make sure that the vehicles can complete their missions with as little extra margin as possible, at the same time being able to handle unexpected situations dynamically.

The main technical challenge is regarding driving range. As energy consumption depends on several factors, such as road topography, speed profiles and weight, determining the distance possible to be driven is a complex problem. As an example, the electric bus running line 55 in Gothenburg needs double the amount of energy when driving in one direction compared to the other. Therefore, to maximize the use of the vehicle it is necessary to plan and follow up the trips with intelligent energy consumption prediction and adaptive route planning.



This project was a continuation of the project EL FORT – Electric Fleet Optimization in Real Time. In that project a PhD student started working on the development of energy estimation and routing algorithms for electric commercial vehicles towards his Licentiate degree. In this project, the student focused on machine learning and developed further the methods from the previous project.

4 Purpose, research questions and method

The main purpose of this project was to develop methods to plan routes that minimize energy consumption of Electric Commercial Vehicles (ECV) for urban logistics, taking into account uncertainty. Considering their battery capacity, the goal is to make sure they will be able to drive the complete routes, even managing unexpected situations. In order to do that it is necessary to estimate energy consumption while planning the routes. Charging stops should be planned whenever needed in an anticipative way. The basic problem is derived from the Vehicle Routing Problem (VRP), which will be explained in the following chapters.

Some of the typical parameters considered in the VRP literature for estimating energy consumption are vehicle and payload weight, road topography and speed (usually average). However, several other parameters are typically not considered, such as auxiliaries (e.g. air conditioning, fridge unit), a more precise powertrain efficiency and detailed speed profiles (e.g. time-dependent congestion, acceleration and braking). 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.

Uncertainty is another relevant aspect to consider while routing electric vehicles. In this case, the primary uncertainty is energy consumption due to many stochastic factors such as traffic conditions and driving behaviour. Additionally, in more dynamic transport operations, there might be changes to the plans when the vehicle is already en route. Therefore, the route should be planned in a predictive way, especially when planning charging stops.

The main research questions investigated in this thesis are:

- How can accurate energy consumption prediction be integrated into route planning for electric commercial vehicles?
- How can urban freight transport missions be accomplished under uncertain energy consumption and avoiding battery depletion?
- How can dynamic changes in transport missions be anticipated while planning routes and charging?

In order to tackle uncertainty and make the methods adaptable to different realistic scenarios, Machine Learning (ML) has been the main approach. For energy prediction, a Bayesian Machine Learning method is proposed in order to learn from real data and be able to predict variance. As solution method, a Reinforcement Learning (RL) is proposed to minimize the risk of battery depletion while planning the routes dynamically. An overview of these techniques is provided in the following chapters.

There was a significant effort to validate the methods being developed using realistic cases. For the energy estimation, a high-fidelity vehicle model was used as benchmark and the results from the developed models were compared with precise simulations. The road network of Gothenburg was used in the first article. In the second and third, a realistic traffic scenario for the city of Luxembourg was used for the simulations. Additionally, logged data from buses driving in Gothenburg was used for validation.

5 Objectives

The scope of the project was to research methods and algorithms that are enablers to answer the research questions above. The main objectives are:

1. Develop an intelligent stochastic method for energy consumption estimation and route planning for electric commercial vehicles. Maximize the use of the battery capacity and driving range, increasing customer confidence in using electric trucks. Increase efficiency for the complete fleet in terms of energy and time, potentially reducing operational costs for the transport companies. Function as the core enabler for the pre-trip and pre-sales applications.
2. Develop an intelligent dynamic routing model that follows up battery state of charge and traffic conditions in real-time to support the driver and reduce range anxiety. Be able to react quickly when facing unpredicted events and plan for additional charging when necessary. Function as the core enabler for the on-trip application.
3. Implement and evaluate the methods. Collect data for assessment and fine tuning of the methods developed. Implement initial demonstrators for the pre-trip and on-trip applications. Document the results.

6 Results and objectives fulfilment

The main results of the project are the two papers published, also fulfilling the objectives above. The deliverables listed in the project proposal were delivered accordingly. There were delays in the project schedule, first due to other activities by the PhD student and then by the short-term lay-offs due to the pandemic. However, the doctoral student was able to complete his studies and the defence was on the 18 of February 2021.

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	X	Results from the project are currently being applied in product development by Volvo
Introduced to the market		
Used in investigations, regulations, permit matters/political decisions.		

7.2 Publications

Paper 1

Rafael Basso, Balázs Kulcsár, Ivan Sanchez-Diaz, Electric Vehicle Routing Problem with Machine Learning for Energy Prediction. Transportation Research Part B: Methodological 145 (2021) 1--32. doi:10.1016/j.trb.2020.12.007

This paper first presents a probabilistic machine learning method for link-level energy consumption prediction. It uses Bayesian regression with a prior based on vehicle dynamics and a posterior improved by collected data. The prior is calculated based on map data such as distances, topography and speed profiles as well as a simplified vehicle model to take into account powertrain efficiency. The posterior improves the accuracy of the prediction and makes it possible to compute the variance of energy consumption for each road link. Therefore, factors that are hard to predict such as traffic conditions are embedded in the variance. With this model, it is possible to estimate energy consumption for the road links, paths and routes.

Energy prediction is then integrated into the path finding and routing models. Using the variance, the models include chance-constraints for charge planning. In this way, it is possible to plan charging within a confidence interval. For instance, chance-constraints could state that the battery level should not get below 20% with 95% confidence, which means that there is only a 5% risk that the battery level will get below that threshold. Partial recharging is also considered in order to save time.

The validation of the energy model is done using a high-fidelity vehicle model connected to realistic traffic simulations, as well as real data from buses. The routing model is compared with a deterministic VRP similar to the ones in the literature. Results indicate high precision for the energy model as well as energy savings and increased reliability for the routes.

Paper 2

Rafael Basso, Balázs Kulcsár, Ivan Sanchez-Diaz, Xiaobo Qu, Dynamic Stochastic Electric Vehicle Routing Problem with Safe Reinforcement Learning. Submitted to Transportation Research Part E: Logistics and Transportation Review.

This paper introduces the Dynamic Stochastic Electric Vehicle Routing Problem (DS-EVRP) as a Markov Decision Process. It defines a state representation, set of valid actions and a state transition function. The model focuses on a single vehicle with dynamic customer requests and stochastic energy consumption.

The proposed solution method is based on Safe Reinforcement Learning. A Value Function Approximation is presented with a look-up table referenced by a reduced state representation. A two-layer safe policy is shown with chance-constraints to minimize the risk of battery depletion while driving. Furthermore, a training approach is introduced with a rollout heuristics to improve the learning process.

Numerical experiments are performed to evaluate the performance of the proposed solution method. It is compared with a simple reoptimization method. Energy consumption is sampled from the distributions learned in the previous paper. The results show potential energy savings while avoiding the vehicle running out of battery.

PhD thesis

Rafael Basso, Energy consumption estimation and routing for electric commercial vehicles – a probabilistic machine learning approach, February 2021.

The thesis focuses on the development of energy consumption prediction and routing methods for electric commercial vehicles. The first part presents an overall background and short state of the art review. The main contributions are presented in the second part. The included articles are a step-by-step development of the methods, each covering different aspects of the problem. The first paper presents a deterministic energy prediction model integrated into routing models. The second paper proposes a probabilistic energy estimation method based on Bayesian machine learning and adds chance-constraints into the routing problem in order to plan charging within a confidence interval. The third paper covers routing with dynamic customers and stochastic energy consumption, proposing a solution method based on Safe Reinforcement Learning to minimize the risk of battery depletion by planning charging in an anticipative way. All papers are validated with realistic simulations as well as logged data. The results indicate that it is possible to save energy and reduce the risk of running out of energy while en route.

8 Conclusions and future work

Electric Commercial Vehicles are currently gaining momentum. Several vehicle manufacturers have 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 future regulations from various countries. 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 transport 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. The three papers are a step-by-step development in an effort to answer the research questions. They introduce methods for accurately estimating energy consumption and its variance, in this way capturing uncertainty. These methods are then integrated into routing models in order to compute routes that are feasible for the vehicles, adding charging stops within a confidence interval to reduce the risk of battery depletion. Finally, dynamic events are taken into account in a solution method that plans routes in an anticipative way.

Careful validation was performed taking into account realistic scenarios. The results indicate that the methods produce routes that are both more reliable and require less energy. With that in mind, they are seen as potential enablers for achieving the benefits of electric commercial vehicles.

9 Project participants

Participant	**Role and area of responsibility**	**Personnel and other resources**
Volvo GTT	PhD student	Rafael Basso
Chalmers – Electrical Engineering	PhD supervisor	Balazs Kulcsar
Chalmers – Technology Management and Economics	PhD co-supervisor	Ivan Sanchez-Diaz

Listed above are the main participants in the project. Other persons at Volvo and Chalmers were involved in parts of the project work.