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Fixed Route Refueling-Strategy For Fuel Cell Trucks

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Abstract

Road logistics are essential to ensure the smooth flow of production and delivery of goods to their destination. Heavy-duty transportation places high demands on the power supply and driving range. Fuel cell electric powertrains appear to be the most suitable solution in the context of zero-emission targets for long-haul trucks. While several companies are working on the development of drivetrains and vehicle concepts, the supply of the required hydrogen remains a challenge. Many uncertainties in the logistics industry are caused by the lack of hydrogen fuel stations. This paper presents a concept to detect suitable hydrogen fuel stations along a planned route and select those that minimize hydrogen consumption. The concept is applied to a known set of fuel stations in Germany and a fixed route defined by the operational task of the truck. First, fuel stations that are relevant to the operational task are identified. Then, the energy consumption of the refueling strategy is minimized by solving the fixed-route vehicle-refueling problem (FRVRP), taking into account vehicle characteristics and unknowns such as the precise distance to the refueling station. An external application programming interface provides the route information. The optimization is then implemented as a mixed integer program (MIP). The resulting strategy indicates the sequence of fuel stations that need to be visited to reach the route destination in the most energy-efficient way. The implementation of the strategy shows that the operation of heavy-duty hydrogen vehicles in Germany is feasible with certain boundary conditions. Therefore, integrating the refueling strategy into the navigation task to avoid running out of fuel is a step towards reaching the zero-emission targets.

Keywords

hydrogen refueling strategy; hydrogen fuel stations; fixed-route vehicle-refueling problem; fuel cell; heavy-duty truck

1. Introduction

Compared to the refueling problem for vehicles with internal combustion engines or hybrid powertrains, fuel station planning for vehicles with fuel cell (FC) electric powertrains has different challenges. While fuel cost is of interest to operators of conventional trucks [1], keeping the vehicles in operation is an issue for alternative-fueled vehicles [2]. This is due to the lacking amount of fuel stations for alternative fuels and the limited range of vehicles [2]. Germany for example, has 91 operational hydrogen fuel stations, at 700 bar level, by May of 2023 [3]. Out of these, only about ten stations are accessible for trucks [4]. To ensure operability, it is compulsory to combine the navigation of the truck with its fuel planning. Otherwise, there is a risk of running out of fuel and not being able to reach a refueling station. To ensure operability and make FC trucks attractive for operators, an energy management system (EMS) that minimizes hydrogen consumption is developed. The EMS is designed to control the power supply from the FC to the powertrain of the truck. Therefore, it is integrated into an onboard system running in the truck. To ensure the operation of the system and prevent transmission errors, the amount of data transmitted should be as small as possible. The navigational data is supplied by a web API with a response with a high data load. Therefore, the number

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of these requests needs to be limited. Hence, it is an attractive approach to solve the refueling strategy to provide the required amount of hydrogen as an FRVRP.

In this paper, we present a method to solve the FRVRP for FC trucks, defining suitable fuel stations in the first step and deriving a policy, that considers the limited amount of fuel stations and the fuel consumption on the track afterward. First, an overview of the literature is given. Thereafter, the problem is introduced in detail and an approach to solve is presented. We show how an FC truck operation in an environment with fewer refueling stations can be ensured and where further improvements can be made.

2. Literature review

Vehicle routing problems (VRP) try to find a policy that either minimizes one or several route properties, those are e.g. travelled distance [5], fuel costs [5], [6], or aims to fit the routing into a time window [7]. These methods can solve the routing and refueling problem as a whole. To do so, a graph network is required. As this is not available, the “route-first, refueling-policy second” approach [8] is used. This approach solves the routing problem in the first step. Thereafter, the refueling problem is solved for the resulting fixed route. The fixed-route vehicle-refueling problem (FRVRP) divides the route into edge segments that are connected by nodes [9]. Depending on the model, the fuel stations are either assumed to be located on the route, represented by the nodes, or extra miles detouring from the route to the fuel stations are considered [10]. Usually, the edges contain travel distance, travel time, and fuel consumption, whereas nodes can be equipped with data regarding fuel prices and fuel levels [9]. Different approaches, models, and aims for solving the FRVRP are presented. [11] differentiates between heuristic, suboptimal, and exact approaches to optimize the cost function. Out of these, only the exact approaches deliver optimal results. These can be divided into mixed-integer programs (MIP) [11] and dynamic programs (DP) [12]. While most optimizers aim to minimize fuel costs by integrating fuel prices at gas stations [8], [9], [13] minimizing fuel consumption is less common [14], [15]. Besides assuming the fuel station to be located on the node, the impact of detouring to the station is considered. While, [8], and [16], assume a priori knowledge of the distance and the consumption from the route to the fuel station and back, [1] models the detour and retour with the possibility of different lengths. In addition to the cost function, the runtime of the FRVRP algorithms is investigated [17].

In literature, the fuel consumed while traveling the route is either assumed to be constant [8], [16], [17] per distance unit or derived from vehicle models [1], [18], [19]. The authors of [20] derive a cost-optimal refueling strategy from [21] and [8], that includes the compulsory rest periods of truck drivers. In [15] the fuel consumption within an FRVRP is reduced considering the additional fuel demand required when driving a full fuel tank uphill. To minimize the fuel cost of a hybrid electric truck, [18] solves the FRVRP using DP. There the vehicle operation is modelled assuming that the hybrid truck can be operated in four different driving modes. An approach to reduce the amount of considered gas stations is presented in [10], by removing the most expensive stations from the solution space, the computational speed is increased.

As presented above the FRVRP is commonly used to minimize fuel costs. Therefore, a constant fuel consumption per distance unit is assumed. Additionally, it is assumed that the amount of fuel stations is large enough to choose between several stations to reduce costs. To the author’s best knowledge, the FRVRP has never been used to derive an operation policy that enables truck operation for FC trucks. Therefore, a vehicle model will be integrated into the pre-processing to precisely estimate the hydrogen consumption.

3. Problem description

At the moment, the availability of refueling capabilities is one major issue, when operating a FC truck [4]. H2-Mobility [3], a platform to push hydrogen mobility, lists 91 hydrogen refueling stations in Germany that are in operation. Because of this low number, refueling needs to be considered when planning the operation. In the concept of the applied EMS, the refueling strategy is computed onboard the truck, and the “route first, refueling-policy second” [10] approach is implemented. This decision was made to reduce the data stream from and to the truck. The route the FRVRP is solved for is determined by an external, web navigation service. Starting from this ‘base’ route, two issues arise regarding the refueling policy of the hydrogen truck. First fuel stations along the planned route need to be determined. Second the refueling policy to enable the operation of the truck needs to be determined.

3.1 Bordering refueling stations

The base route the FRVRP is solved for is structured as a row of subsequent nodes and edges connecting starting point, waypoints, and destination. As discussed earlier in this work and shown in [4], the density of hydrogen refueling stations in Germany is sparse. It is obvious that there are regions with one refueling station in a radius of hundred kilometers. This issue requires the implementation of the refueling stations into the operation policy of the truck. After choosing a route, as discussed in [10], unqualified refueling stops, that enlarge the refueling problem, need to be removed. This prevents potentially long detours which would unnecessarily consume fuel. While most literature regarding the FRVRP assumes variable fuel prices in between refueling station, the hydrogen costs per kilogram is assumed to be the same at all stations, which meets the current market situation [3].

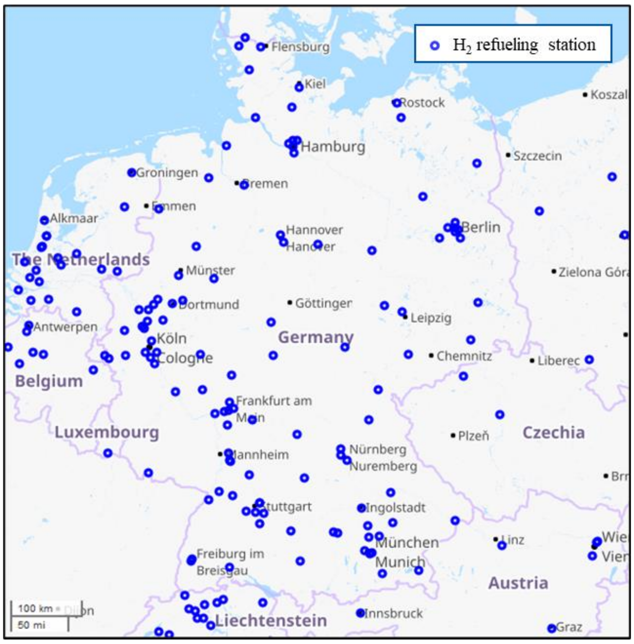

Figure 1: Density and location of hydrogen refueling stations in central Europe [3]

3.2 Refueling policy

After deriving the refueling stations that are located along the route, a policy needs to be found that enables the operation of the truck. FRVRPs operate in a way that the fuel level never falls below the minimum value before reaching a refueling station [9]. Their consumption is usually computed assuming a constant fuel demand per distance unit [1]. This concept is suitable for a policy that is aiming to reduce fuel costs in an environment with a high density of refueling stations, as it is the case for trucks with combustion engines. In that case, running out of fuel can be prevented by targeting a closer refueling station than planned. This leads to higher fuel costs but not to run out of fuel. In a network with a low density of refueling stations, this is not possible. Therefore, to ensure operability, fuel consumption needs to be calculated precisely.

As described above, the aim is to limit the amount of exchanged data. Due to this decision, it is unintentional to request the distance of the detours of all refueling stations that are located along the route from the web

API. Hence the distance between the node and the refueling station of the detour needs to be estimated. The quality of this estimation is afflicted with an error. The total distance and consumption error of the estimation of the detour correlates with its length. Therefore, determining the nearest refueling stations and thereby minimizing the detours reduces this error.

4. Model formulation

To derive the refueling policy the bordering refueling stations and their approximate distance to the route need to be calculated. Thereafter, the FRVRP with the truck model can be solved. The location of the refueling stations as well as the base route from start to destination are known. As described above, the base route is supplied by a web navigation service, that returns the route as a sequence of subsequent nodes and edges attached with meta information regarding distance, travel time, gradients, and location of the nodes.

4.1 Deriving bordering refueling stations

The route, which the refueling problem should be solved for, is defined by a starting point (s), waypoints that should be visited in a predefined order, and a destination (e). The route is given by a sequence of nodes ($n_{s \leq i \leq e}$) that are separated by the exact same distance. Besides the distance (d) between the nodes, the gradient (g), the assumed travel speed (v), and its specific longitude ($long$), as well as its latitude (lat), are attached to the node. The data containing these values is supplied by the web API. Each node is structured as follows: $\overrightarrow{n_i} = \{d, g, \mathrm{v}, \mathrm{long}, \mathrm{lat}\}$.

Since fuel costs per kilogram are the same for nearly all refueling stations, the stations that are closest to the route are of relevance. Each station that is not bordering the route would lead to unnecessary fuel consumption. Therefore, they are removed. A bordering fuel station is defined as the station that is nearest to a least one node of the route. To determine those stations, the beeline between each node and each station is computed as shown in Figure 2. On the left side of Figure 2, these bordering stations are marked by blue lines. The information on the closest station and the distance are attached to the node. As one station is the closest one in a particular area, it is the closest one to all nodes in the area. Out of these consecutive nodes, one is the closest to the station. Since the route information is known, while the precise detour information is not, minimizing the detour distance reduces the error in the detour approximation. In the following step, the node that is the closest one to a refueling station within a pattern of consecutive nodes is determined. This allows for transforming the route into a sequence of nodes that are the closest to the refueling stations and edges that represent the route from the start via these nodes to the destination. The right side of Figure 2 illustrates the result of calculating the nodes that are the closest to a station of each pattern of nodes. This data set allows solving the FRVRP with a truck model to determine the hydrogen consumption.

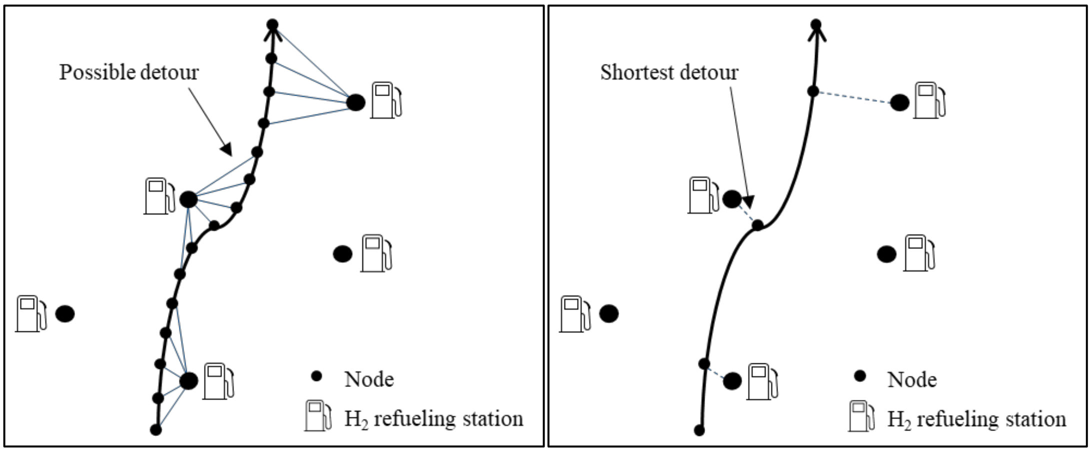

Figure 2: Determination of the closest refueling stations to each node of the route (left); closest node to a refueling station of a pattern of nodes (right)

4.1 Modell of the FC truck

Approaches that solve the FRVRP as presented in [8] and, [11] try to minimize fuel costs in environments with variable fuel costs. Solving the FRVRP with fuel spending as the optimizations cost function minimizes hydrogen consumption as well. To include a precise model of hydrogen consumption into the model, the required energy of the truck and therefore, the power by the engine is determined. The nodes (n) supply the data to compute the forces acting on the truck. Those are the air drag (1), the rolling resistance (2), the slope force (3), and the inertia of the truck.

$$F_{air} = \frac{1}{2}\,\rho\, c_w\, A\, v^2 \tag{1}$$

The air density (ρ), the air drag factor (c_w) as well as the front surface (A) of the truck are constant. This means the air drag (F_{air}) is mainly a function of the velocity (v) that is predicted along the complete route and stored in n.

$$F_{rr} = m\, g\, c_{rr}\, cos(\alpha); \qquad w. \qquad \alpha = arctan(g) \tag{2}$$

The rolling resistance (F_{rr}) is a function of the gradient (g). The vehicles mass (m), the free fall acceleration of the earth (g) and the rolling resistance factor (c_{rr}) are constant.

$$F_{slope} = m\, g\, sin(\alpha); \tag{3}$$

The drag due to inclines is concluded by the slope force (F_{slope}).

$$F_a = m\, a; \qquad w. \qquad a = \dot{v} \tag{4}$$

The inertia force (F_a) is a function of the vehicle acceleration (a), that is the change in the vehicle's velocity $(\dot{v})$ and therefore a function of the velocity.

$$P = \left(F_{air} + F_{rr} + F_{slope} + F_a\right) v \tag{5}$$

The power (P) required to operate the truck is defined by the sum of all the forces Equations (1 – 4) multiplied by velocity. Following these equations, including the efficiencies of the electric motor, gearbox, and inverter, the actual power required at each node is computed. Integrating this power over the travelled distance, to respect the spatial gradient values, and dividing it by the velocity to transform the spatial values, allows us to determine the energy that is required to pass each edge. Dividing the required amount of energy by the FC efficiency, that is depending on the operational strategy, the hydrogen demand is derived. That way the specific amount of hydrogen required for each edge, considering the assumed velocity and the precise gradients, is computed. These edges consecutively connect the start with the nodes closest to the refueling stations, and the destination. The derived hydrogen demand is added to each of the edges, resulting in a sequence of hydrogen demands in between approachable refueling stations.

To include the energy that is required on the route and to reach the refueling stations the concept of [11] is adapted as suggested. Information on the detours is not determined using navigational methods to reduce the data stream as mentioned before. Therefore, the velocity and distance approaching the refueling station need to be approximated. To do so, the distance is assumed to be approximated by the beeline between a node and its corresponding station, multiplied by a safety factor. This allows us to estimate and include the uncertain length of the detour. The speed of the truck on the detour needs to be approximated as well. There, the truck is assumed to constantly travel with the maximum allowed speed on lower-level roads. The detour is assumed to be of zero gradients. Since the detours, to which this estimation is applied, are those closest to the route, the error is assumed to be small compared to the total power demand.

4.2 The modified FRVRP

The data determined in the previous steps are required to determine the truck's hydrogen demand. Based on that information regarding the refueling stations bordering the route, the refueling strategy is planned. The concept is based on the MIP approach presented in [11]. The constraint regarding the minimum amount purchased is removed since the main target is to enable operation. Additionally, the fuel demands are known. The problem consists of the starting node (s), the nodes (r_i) closest to the determined bordering refueling stations, and the destination (d) derived in the previous step. The index (i) references the nodes from start $(i = 1)$ to destination $(i = d)$. Each node allows a detour to its corresponding refueling station, that requires (fl_i) fuel. There the amount (ref_i) can be refueled. The decision to take the detour and refuel is based on the variable dec_i. dec_i equals one if the detour is made, otherwise, it equals zero. Each edge connecting the nodes requires (f_i) hydrogen, while the fuel level of the truck at each node is given by (l_i). The minimum hydrogen level (l_{min}) allows to have some reserves to counteract errors and compensate for possible unplanned detours. The maximum hydrogen level (l_{max}) is defined by the dimensions of the hydrogen tanks. Since the consumption of each edge and each detour is known explicitly, the MIP writes as follows:

$$min \sum_{i=1}^{d} ref_i \tag{6}$$

With the constraints:

$$l_{min} \leq l_i + fl_i * dec_i - ref_i \tag{7}$$

$$0 \leq ref_i \leq (l_{max} - l_{min}) * dec_i \tag{8}$$

$$l_{max} \geq ref_i + l_{i-1} - f_i - fl_i * dec_i \tag{9}$$

$$l_i = l_{i-1} - f_{i-1} - 2 * fl_i * dec + ref_i \tag{10}$$

$$f_1 + fl_1 \leq l_s \leq l_{max} \tag{11}$$

$$l_d \geq l_{min} \tag{12}$$

$$dec_d = ref_d = 0 \tag{13}$$

Objective (6) minimizes the refueled amount of hydrogen. That way the time and distance of the detours while enabling vehicle operation in minimized also. Constraint (7) ensures that the fuel level does not fall below the minimum allowed. Constraint (8) limits the refueling capacity of the truck relative to the tank volume and defines it as a positive integer. The refueling capacity based on the previous consumption is defined in constraint (9). The fuel level after potential refueling is calculated in equation (10). Constraint (11) defines the fuel level required at the start of the trip. While constraint (12) limits the fuel level when arriving at the destination. The destination constraint (13) prevents potential refueling at the destination node and defines the decision variable and the refueled amount of hydrogen as zero. Refueling for a potential upcoming route is not considered.

If solving the MIP is possible, hydrogen trucks can be operated on the route using the resulting stations of the problem solution. Assuming that the travel speed on the predefined route is higher than the speed on the detours, solving the MIP also minimizes the required time for truck operation. If the MIP is infeasible, operation on the route with the defined minimum hydrogen level and the total fuel capacity of the truck is not possible. In that case either a truck with a larger tank volume needs to be used or the route needs to be changed.

5. Results

The refueling strategy is developed in the SeLv project. The project aims to develop a modular FC electric drivetrain for heavy-duty trucks. The key parameters of the truck are concluded in Table 1. Regarding the network of hydrogen fuel stations at $700\ bar$ level in Germany, some assumptions were made. First, it is assumed that each fuel station can supply the requested amount of hydrogen at any time. Second it is assumed that the stations are accessible for a $41\ tons$ truck. Third, fuel stations under construction are included in the computation. In the following section, the influence and density of the bordering fuel stations are reviewed. Thereafter, the power demand along the route and on the detours is computed. The results of the combined method including the solution of the MIP are discussed in conclusion. There the necessity of a refueling policy for areas with a low density of refueling stations is discussed as well. The policy is reviewed along the testing route of [22] in southern Germany at a length of 342 km. To demonstrate the concept of refueling policy tank capacity was reduced to a fiction value of 12 kg.

Table 1: Key parameters of the SeLv FC truck

Characteristic	Value
Mass	41 tons
Front area	9,94 m^2
Gearbox efficiency	0,95
Electric engine efficiency	0,95
Inverter efficiency	0,95
Auxiliary power demand	15 kW
Tank capacity	68 kg

5.1 Bordering fuel stations

Starting with the route information in a first step the distances between all refueling stations and each node are computed. This step is visualized in the very left map of Figure 3. There the refueling stations closest to each section of the route are marked by a Roman numeral. The areas of the route where a specific refueling station is bordering are marked by a Roman numeral in a white circle. In the specific example, the number of refueling stations that needs to be considered reduces to 7 stations. These have a strongly varying distance to the route. While some stations are in direct proximity to the route, the distance to the closest station reaches values up to 37 km in some sections. In this example, station II is the closest one to a section of the route at a beeline of around 35 km as visualized at the right map of Figure 3.

5.2 Computation of hydrogen demand

After determining the nodes for the potential detours, the hydrogen required for the edges and the detours is computed. This is done by solving the vehicle dynamics equations with information regarding velocity and gradients. The hydrogen demand per edge reaches up to 8 kg while the total trip requires ca. 33 kg of hydrogen. Additional to the edges, up to ca. 2 kg of hydrogen is scheduled to reach refueling station II. The hydrogen consumption to reach each node and the potential refueling station is summarized in Table 2. There the hydrogen demand required to travel an edge is presented in the second column. The additional demand that is consumed when choosing to refuel is summarized in the third column.

5.3 Refueling policy

The MIP is applied to the values of Table 2. Minimizing the overall hydrogen consumption, the MIP schedules three refueling stops. The resulting overall refueling strategy is visualized in the right map of

Figure 3. The detour to refueling station IV is easy to identify, while the detours to stations III and V are difficult to recognize as they are very close to the route.

Table 2: Hydrogen demand of the route and the potential detours

Node closest to	Hydrogen demand from the previous node	Hydrogen demand to station
Station I	0 kg	0,04 kg
Station II	3,11 kg	1,88 kg
Station III	3,53 kg	0,02 kg
Station IV	8,43 kg	0,32 kg
Station V	8,10 kg	0,04 kg
Station VI	6.04 kg	0,68 kg
Station VII/Destination	4,24 kg	0,51 kg

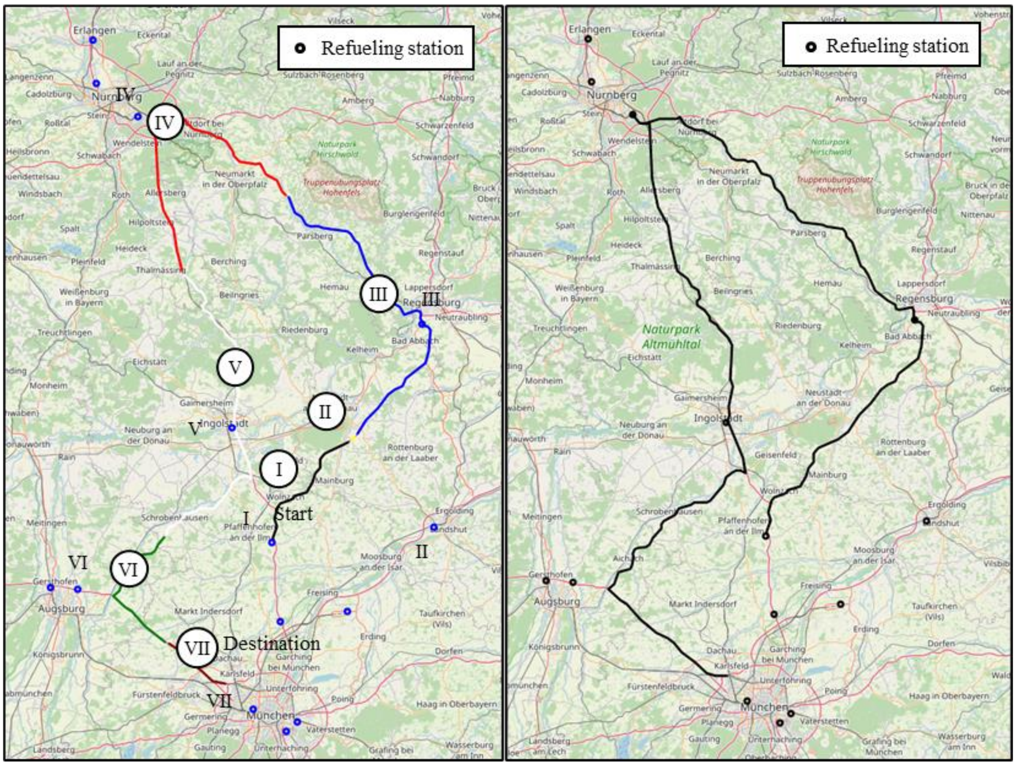

Figure 3: Process of deriving the refueling strategy; deriving the closest refueling stations (left); the overall refueling policy integrating hydrogen consumption (right)

6. Discussion

Applying the policy allows for a potential reduction of hydrogen demand by avoiding long detours to refueling stations. Drivers and fleet operators are provided with a strategy that gives them certainty about the existing supply of hydrogen, visualized by an HMI in the truck, and thus enables smooth and hassle-free operation. Integrating the hydrogen demand from the FC operation strategy into the policy returns a precise estimation of the fuel consumption and therefore supports a qualitative selection of the optimal refueling station. Determining the refueling stations closest to the route allows for the selection of the optimal station possible as well. We can show, that by implementing the presented method it is possible to operate FC trucks all over Germany as the gaps between the refueling stations can be overcome easily with knowledge of the station’s locations. As discussed before the derived refueling stations need to be targeted to ensure operability in the sparse network of hydrogen refueling stations. Overall, this policy and the generated strategy will help enable hydrogen truck operation on German roads.

7. Conclusion

In this paper, the issue of operating FC trucks in an environment with a sparse refueling station density is addressed. It is shown that most research focuses on diesel trucks with a high density of refueling stations and that predominantly the fuel consumption is assumed to be constant per distance unit. The problems of the bordering refueling station and the subsequent refueling policy are discussed. To determine the closest station to the route, the beeline between each node and each refueling station is computed. Based on the set of bordering refueling stations the optimal refueling strategy is derived, solving the refueling problem as an MIP. This way it is shown that it is possible to operate FC trucks on German highways when considering the locations of the refueling stations.

Acknowledgments

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Biography

Achim Kampker (*1976) is head of the chair “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University and is known for his co-development of the “StreetScooter” electric vehicle. Kampker also acts as a member of the executive board of the “Fraunhofer Research Institution for Battery Cell Production FFB” in Münster. He is involved in various expert groups of the federal and state governments.

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Fabian Schmitt (*1980) is the division manager responsible for the zero-emissions trucks projects at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University. He is co-developer of the electric vehicle “StreetScooter”.

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