Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Short Communication

An efficient online mapping tool for finding the shortest feasible path for alternative-fuel vehicles

Michael Kuby [a,*], Ozgur M. Araz [b], Michael Palmer [c], Ismail Capar [d]

[a] Arizona State University, School of Geographical Sciences and Urban Planning, Mail Code 5302, Tempe, AZ, 85287-5302, United States
[b] University of Nebraska Medical Center, College of Public Health, Box 984365, Omaha, NE, 68198-4365, United States
[c] Progressive Insurance, 6055 Parkland Blvd, Mayfield Heights, OH, 44124, United States
[d] Texas A&M University, Industrial Distribution Program, 3367 TAMU, College Station, TX, 77843-3367, United States

ARTICLE INFO

Article history:
Received 5 March 2014
Received in revised form
20 August 2014
Accepted 21 August 2014
Available online 26 September 2014

Keywords:
Alternative fuel vehicles
Shortest path problem
Refueling
Routing
Driving range
Web GIS

ABSTRACT

Infrastructure for fuel-cell and other alternative-fuel vehicles is lacking not only in the paucity of fuel stations, but also in inadequate web-based support to help drivers complete their trips via the few stations that do exist. In this paper, we present an online mapping tool for finding the shortest feasible path in a road network given the vehicle's driving range and station locations. Users input their origin, destination, type of fuel, and driving range, and the algorithm generates a new reduced feasible network in which the vertices are the origin and destination nodes and reachable fuel stations and the edges represent feasible paths between them. Dijkstra's shortest path algorithm is applied to this reduced network to find the shortest feasible path. Efficiency is substantially improved by pre-processing and storing the shortest-path distances between stations. We present a web-mapping prototype (www.afvrouting.com) for hydrogen and compressed natural gas stations in the United States. Sample results illustrate the need for this kind of globally optimal solution method by showing that the optimal feasible path and refueling stops can vary tremendously as a result of user inputs for driving range, initial tank level, and one-way or round-trip.

Introduction

Optimization models dealing with hydrogen refueling infrastructure can be grouped into three categories aimed at three different sets of decision-makers. Supply chain models [1,2] optimize the integrated system of feedstock supply, production, distribution, and retailing, and are especially valuable for coordinating across sub-sectors of the industry and at examining

* *Corresponding author*. Tel.: +1 480 965 6850; fax: +1 480 965 8313.
E-mail addresses: mikekuby@asu.edu (M. Kuby), ozgur.araz@unmc.edu (O.M. Araz), emdypl@gmail.com (M. Palmer), capar@tamu.edu (I. Capar).
http://dx.doi.org/10.1016/j.ijhydene.2014.08.104

the tradeoffs between centralized and distributed production methods. Refueling facility location models [3,4] are aimed at fuel retailing companies trying to plan the most convenient network of stations to serve drivers. This paper addresses the third category of hydrogen infrastructure models, developed to help drivers plan their routes using the existing stations [5–9].

Due to the lack of a widespread refueling infrastructure and the limited driving range of vehicles, the task of finding stations and planning efficient routes is a major challenge for early adopters of alternative-fuel vehicles (AFVs) [10,11]. To address this need, several public and private organizations around the world have developed AFV routing websites [12,13]. Using these online tools, drivers input their origin, destination, and fuel type, and the websites output the shortest path and show AFV stations near that path. Users can scan the map for promising stations, manually add intermediate stops (known as waypoints), and recalculate a new path via the chosen waypoints. With most of these sites, determining whether a feasible path exists and finding the optimal one requires a cumbersome trial-and-error process to manually check the feasibility of each trip leg, try a different set of intermediate stations, and repeat until satisfied. One website for compressed natural gas (ww.gibgas.de/Tankstellen/Umkreissuche Routenplaner) comes significantly closer to the goal but still falls short of global optimality [14]. It allows users to specify a driving range and a starting tank level as well as a buffer of up to 15 km around the shortest path. It then selects the stations that enable the shortest feasible refuelable path *within that corridor*. There remains an urgent need for practical online algorithms to find and display the *globally optimal shortest feasible path* with a single click, where feasible means the driver would not run out of fuel given their vehicle's driving range. Note that we use the terms "fuel" and "tank" here to refer to any form of energy and energy storage, including electrical charge and battery.

Several recent papers [5–9] have developed computationally efficient algorithms to solve similar problems. These methods, however, have not yet penetrated the alternative-fuels industry, nor have the papers included methods for implementing them in a web-mapping environment. In this paper, we aim to bridge the gap between the operations research literature and industry by adapting the methods in Refs. [5–9] to satisfy the basic requirements of early AFV adopters. We explain how to implement an efficient, globally optimal algorithm in a web GIS environment, and demonstrate a prototype for hydrogen and CNG stations in the United States.

Problem definition and solution algorithm

The network reduction solution method presented here is a simplified version of algorithms developed in the operations research literature by Soedarmadji [5], Khuller et al. [6], Lin et al. [7], Suzuki [8], and Adler et al. [9] for different versions of the "gas station" or "fuel optimizer" problem. In these problems (aimed primarily at commercial vehicles), the goal is to find the optimal path on a network, usually between a single origin and destination, on which a vehicle with the given tank capacity will not run out of fuel. The models differ in terms of optimization criteria (minimize distance or travel time [5], fuel cost [6], combined cost [8], or driver's range anxiety [9]) and types of deviations allowed (fixed route [7], retrace detour from fixed route [8], or fully flexible routing [5,6,9]). Our method minimizes distance or travel time and allows fully flexible one-way or round-trip routing beginning with a full or partly full tank. In addition, it stands out from the papers above by including instructions for an online GIS interface.

We assume a network, G (V, E), with a set of vertices V and edges E. We are given a set of stations, $1,2,\ldots,n$, for alternative fuel type f, $S_f = \{S_{1f}, S_{2f}, \ldots, S_{nf}\}$. Users input their origin O, destination D, type of fuel f, vehicle driving range R, the starting tank or battery percentage α, and whether the trip is one-way or round-trip. The problem is to find the shortest feasible path for the given road network, stations, and user inputs. We can think of the optimal trip as composed of distinct legs or segments. The first leg must connect O to a station using a path not longer than αR. The intermediate legs, if needed, must connect from one station to another using a path not longer than R. The final leg must connect the last station to D via a path not longer than R (for a one-way trip) or $R/2$ (for a round trip).

The algorithm assumes that energy consumption per mile is uniform across all edges and identical in both edge directions. The round-trip assumption that vehicles must arrive at the destination with at least $R/2$ fuel remaining ensures that the vehicle can turn around and reach the last station on the way back [15].

Following [5] and [6], the solution method is based on generating a simplified artificial network on which travel is by definition feasible given the vehicle range. The vertices of the simplified feasible network include only the origin O, destination D, and those fuel stations that are reachable to O, D, or each other given the range. The edges of the feasible network represent paths that satisfy the range constraints. Then, to find the shortest feasible paths for the vehicles for any given O-D pair, we simply apply Dijsktra's algorithm [16] on this artificial feasible network. Fig. 1 illustrates the concept using a small example network adapted from Ref. [17].

The logic of the algorithm is diagrammed in Fig. 2. These steps are explained in detail below, including methods for online GIS implementation. Our web GIS prototype (www.afvrouting.com) uses Google Maps®, but could also be implemented using other customizable routing web sites such as Bing® Maps. The prototype also uses PostgreSQL with PostGIS, Google Maps® Javascript API, PHP web language, and a PHP implementation of Dijkstra's algorithm.

Step 0: Preprocessing and Storage

Following [18], a large portion of the computational burden can be preprocessed in advance and be ready to use whenever a user submits a query. Using the complete street network G (V, E) and the set of stations S_f for fuel type f, we compute a complete inter-station distance matrix by submitting queries for each O-D pair to Google® API. Each of these matrices defines a network G_f (S_f,E_f), in which the set of edges E_f represents the shortest-path distances between each pair of stations of type f. These matrices need to re-computed only when a station or road is added or subtracted from the database, which can be done regularly using a PHP form.

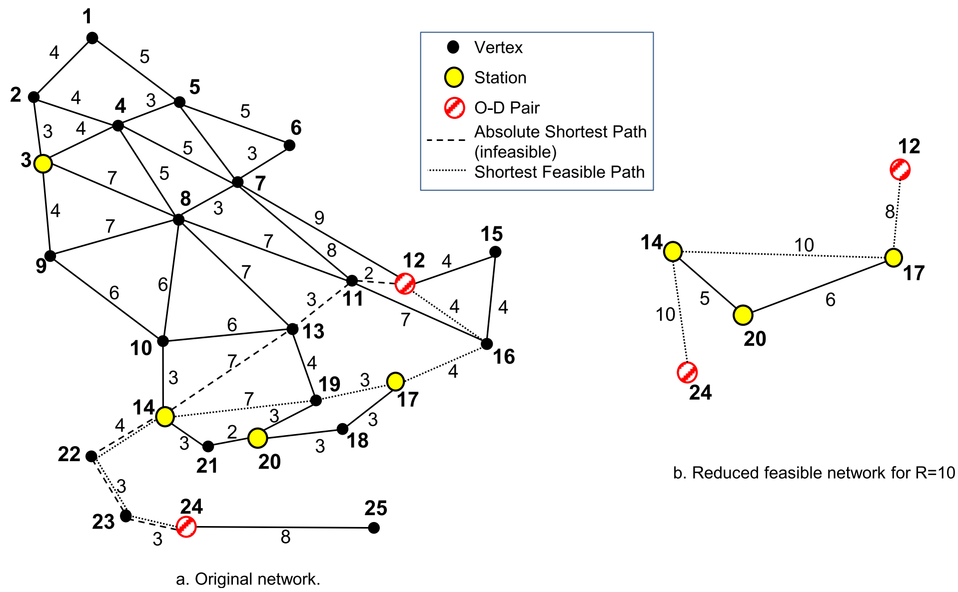

Fig. 1 – Illustration of the reduced feasible network approach for a driving range of 10. (a) On the full network, the absolute shortest path is 22 units long but is infeasible because the distance from the origin (node 12) to the first station (node 14) exceeds the range. (b) Assuming a one-way trip starting with a full tank, the reduced feasible network includes edges representing all feasible paths between stations and from stations to the origin and destination. All paths on this network are by definition feasible. The shortest path is 28 units long and stops at stations 17 and 14.

Step 1: Define the Feasible Network

1a. *Read the user inputs:* O, D, f, R, α, and whether trip is one-way or round-trip. Inputs are entered into a user interface using an HTML form, and location data are processed with Google®'s geocoding service [19], which converts the place name to latitude–longitude co-ordinates (see Fig. 3, top).

1b. *Define an augmented set of vertices*. Load the pre-processed inter-station distance matrix $G_f(S_f,E_f)$. Define $S_{f'} = \{O, S_{1f}, S_{2f} \ldots, S_{nf}, D\}$ by adding rows and columns for O and D to matrix G_f. At the end of Step 1b, G_f contains all shortest path distances between pairs of stations, while cells for distances from O and D to stations are empty.

1c. *Determine the feasible edges and complete the feasible network matrix:* First, execute an SQL spatial query to find all stations within αR Euclidean distance of origin O. Using a Euclidean circle here allows the driver to travel backwards if necessary to find a feasible path, and

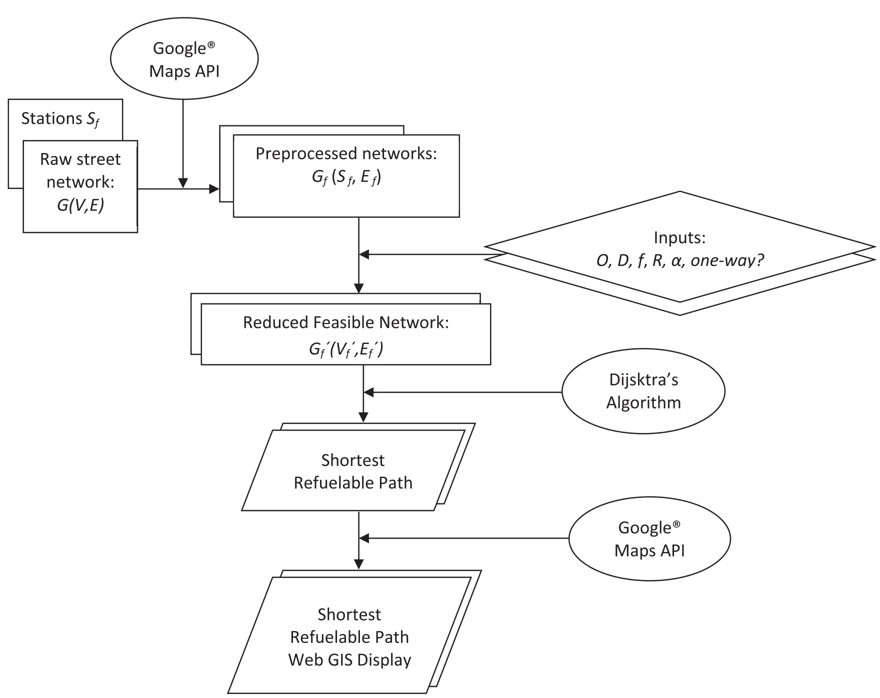

Fig. 2 – Flowchart of solution algorithm.

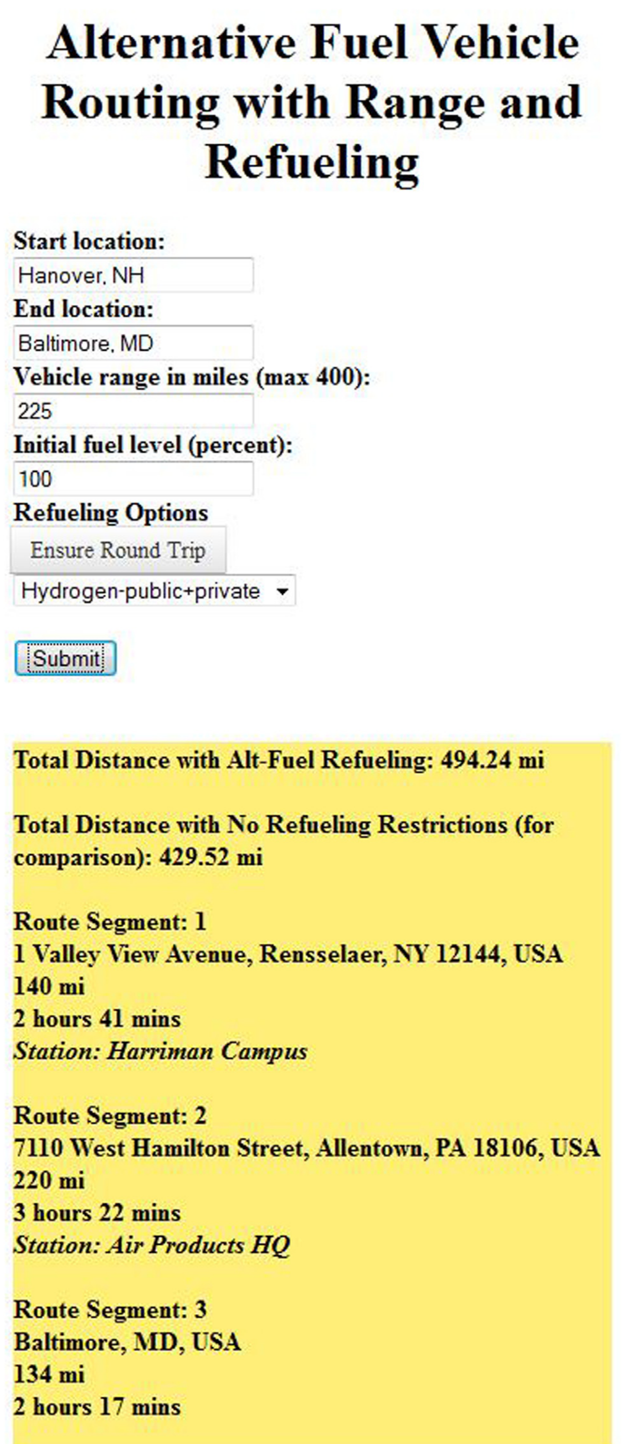

Fig. 3 – User interface (top) and text output (below) from prototype for hydrogen scenario in Fig. 4b.

reduces the number of driving distance queries to be calculated. Second, compute the shortest driving distance from O to the selected stations using Google® directions API. Third, add the path lengths as edges in the artificial network table if the driving distance from O to the station $\leq \alpha R$. Fourth, repeat these three steps to identify and add edges from stations to D if the actual shortest driving distance is $\leq R$ (for a one-way trip) or $\leq R/2$ (for a round trip). Fifth, if either the origin or destination row is blank, report the path as infeasible. Sixth, edit the network matrix to eliminate edges between pairs of stations if length $> R$. Finally, remove empty rows and columns for vertices with no connected feasible edges. The resulting matrix is $G_f(V_f, E_f)$.

Step 2: Solve the shortest path problem.

First, solve the basic shortest path problem from O to D on the matrix $G_f(V_f, E_f)$ using Dijkstra's algorithm [16], which solves efficiently on matrices. Second, use XML to pass the sequence of vertices to Google Maps®, identifying each station stop as a "waypoint" between O and D. Third, generate the route in Google Maps®. Fourth, obtain the distance of each trip leg and generate table display.

Users of online mapping and routing tools have come to expect nearly instantaneous results. The most computationally demanding step—preprocessing the inter-station distance matrix in Step 0—could theoretically be done in $O(|V|^3)$ time using Floyd's algorithm [20], but this does not impact an online user. For each user query, defining the reduced feasible network (Step 1) can be done in $O(|S_f||V|\log|V| + |S_f||E|)$ time, while solving the shortest path problem using Dijkstra's algorithm (Step 2) can be completed in $O(|V_{f'}|\log|V_{f'}| + |E_{f'}|)$ time. The algorithm thus solves in polynomial time and finds exact solutions.

Proof of concept

Our prototype (www.afvrouting.com) currently includes location data for 53 hydrogen stations and 671 CNG stations as of February, 2014, downloaded from the Alternative Fuels Data Center [12]. For prototype purposes, the maximum inter-station length is limited to 400 miles. The pre-processed inter-station networks consist of 2405 edges for hydrogen and 54,257 edges for CNG. We programmed the pre-processor to submit one O-D query every 5 s because overlapping queries sometimes caused problems with the Google® API. Pre-processing therefore took over 3 h for hydrogen and 75 h for CNG. If inter-station distances were not computed ahead of time, some subset of them would have to be computed each time a user submits a query, which would add substantially to the response time. To use the web-based AFV route planner, a user enters the required inputs and clicks "Submit" (Fig. 3, top). After processing, the tool displays the route on a map (Fig. 4) and breaks the route into the individual legs between the origin, each station where refueling is required, and the destination (Fig. 3, bottom). If the trip is infeasible, the tool outputs an error message.

Table 1 provides results for a series of hypothetical scenarios for hydrogen and CNG stations. The hydrogen example is for a hypothetical trip from Hanover, New Hampshire to Baltimore, Maryland, while for CNG the trip is from Redlands to Sacramento, California. These two examples were chosen purposefully to highlight the potentially dramatic effects of changing the range and trip assumptions on the length of the optimal feasible route, the number of refueling stops required, and the route followed. For each example, we impose a series of increasingly restrictive assumptions:

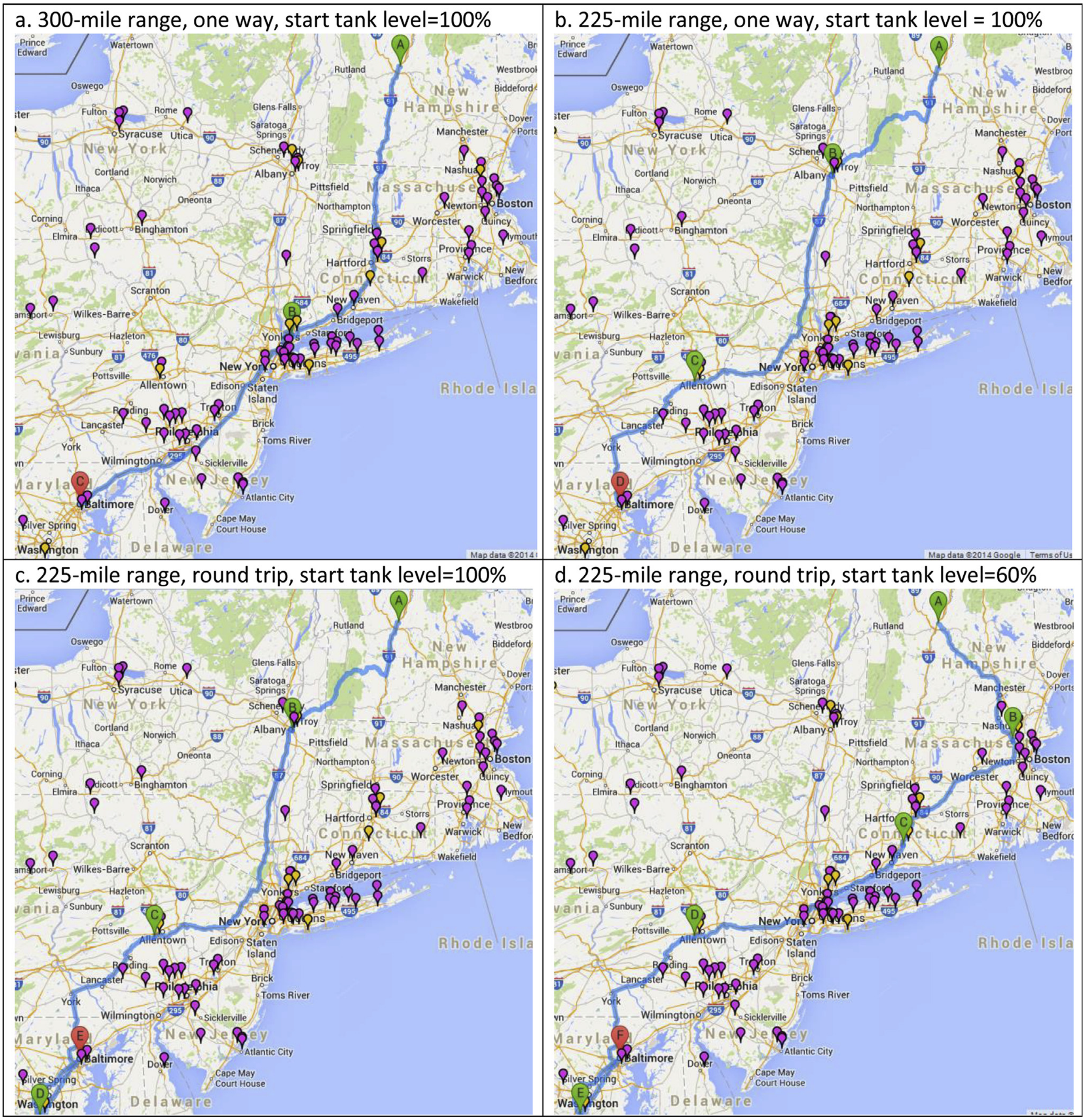

Fig. 4 – Optimal routes from Hanover, NH to Baltimore, MD for hydrogen under various range restrictions.

- the unrestricted route recommended by Google® Maps
- a one-way trip in a hydrogen or CNG vehicle with a 300-mile range
- a one-way trip with a shorter range of 225 miles
- a round trip with the shorter range, which must reach the destination with the tank at least 50% full
- a round trip with the shorter range beginning with a partially empty tank.

The longer 300-mile driving range is approximately the technological highway maximum for the 2014 models, such as the Hyundai® Tucson® Fuel Cell Vehicle and the Honda® Civix® GX natural gas vehicle. The shorter range is illustrative of what drivers today might consider a "safe" driving range with a margin of error for side trips, substandard pump pressure, or lower city miles per gallon. For hydrogen, we assume the availability of all 15 stations in the northeast US, including private stations not currently open to the public, for more illustrative routing options.

Fig. 4 shows optimal routes for four hydrogen trip scenarios. The unrestricted trip (not shown) follows I-91 and I-95 for most of the way, crossing the Hudson River on the George Washington Bridge. With a 300-mile range, the optimal refuelable route detours slightly from I-95 to I-87 to visit a hydrogen

Table 1 – Optimal results for illustrative hydrogen and CNG trips under various driving-range scenarios.

Scenario	Parameter	Hydrogen (public + private stations)	CNG (open to public stations)
	Origin	Hanover, NH	Redlands, CA
	Destination	Baltimore, MD	Sacramento, CA
Gasoline (unrestricted)	Computation time	1 s	1 s
	Path length	430 miles	445 miles
Longer driving range • 300 miles • One–way • Start tank level 100% • End tank level 100%	Computation time	6 s	35 s
	Station stops and length of trip legs (miles)	- to White Plains DPW, White Plains, NY (240 miles) - to Baltimore, MD (218)	- to City of Delano, Delano, CA (201) - to Sacramento, CA (247)
	Total path length	458 miles	448 miles
Shorter driving range • 225 miles • One–way • Start tank level 100% • End tank level 100%	Computation time	3 s	31 s
	Station stops and length of trip legs (miles)	- to RPI Harriman Campus, Rensselear, NY (140) - to Air Products® HQ, Allentown, PA (220) - to Baltimore, MD (134)	- to City of Delano, Delano, CA (201) - to PG&E® Merced Service Area, Merced, CA (134) - to Sacramento, CA (125)
	Total path length	494 miles	449 miles
Round trip • Range same as above • Start tank level 100% • End tank level 50%	Computation time	3 s	29 s
	Station stops and length of trip legs (miles)	- to RPI Campus, Rensselear, NY (140) - to Air Products® HQ, Allentown, PA (220) - to Fort Belvoir, VA (200) - to Baltimore, MD (56)	- to City of Delano, Delano, CA (201) - to City of Ripon, Ripon, CA (183) - to Sacramento, CA (66)
	Total path length	616 miles	450 miles
Round trip starting with less than full tank • Range same as above • Start tank level–see table • End tank level 50%	Start tank level	60%	5%
	Computation time	2 s	9 s
	Station stops and length of trip legs (miles)	- to Nuvera® HQ, Billerica, MA (114) - to SunHydro®, Wallingford, CT (127) - to Air Products® HQ, Allentown, PA (192) - to Fort Belvoir, VA (200) - to Baltimore, MD (56)	- to City of San Bernardino, San Bernardino, CA (10) - to SoCal Gas®, Lancaster, CA (72) - to Clean Energy®/City of Tulare, Tulare, CA (151) - to Clean Energy®/City of Elk Grove, Elk Grove, CA (201) - to Sacramento, CA (18)
	Total path length	688 miles	452 miles

station in White Plains, NY before crossing the Tappan Zee Bridge, adding 6 miles (Fig. 4a). Next, assuming a shorter range (225 miles), the FCV can no longer reach the White Plains station 240 miles from Hanover. The new shortest feasible route increases to 494 miles and stops twice to refuel in Rensselaer, New York and Allentown, Pennsylvania (Fig. 4b). The longest leg is 220 miles between the stations.

Adding the round trip assumption, the previous route is no longer feasible, because the round trip between Allentown and Baltimore would be 268 miles. Now the only feasible route goes 56 miles past Baltimore to Fort Belvoir, VA to refuel before doubling back to Baltimore (Fig. 4c), which illustrates the possible need for backwards moves from the origin or destination. Note that the round trip is not necessarily symmetrical, and in this case a driver would *not* have to return to Fort Belvoir in both directions. After filling once in Fort Belvoir, it is 55.7 miles to Baltimore and 134 miles from there to Allentown, which leaves 35.3 miles of range remaining.

Finally, assuming the tank level starts at 60% full, the algorithm must find a feasible round trip that stops first at a station within 135 miles of Hanover. With Rensselaer no longer within reach, the shortest feasible route now detours through the Boston area to a station 114 miles from Hanover. Starting with the tank half full (112.5 miles) renders the trip infeasible.

The Redlands–Sacramento CNG trip (not illustrated) is noteworthy for the fact that there is little difference in the length of the five optimal routes (445-452 miles), due partly to the greater availability of CNG stations. Yet the route varies significantly in whether it travels up I-5 with no stops vs California Route 138 with one, two, or three stops, and whether it travels east or west around the San Gabriel Mountains. Note that none of the optimal feasible routes for either fuel employ simplistic "there-and-back" deviations off the absolute shortest path, although that could be optimal in certain situations.

The web-based routing tool solves in a reasonable amount of computation time while providing a feasible and optimal route instead of just a list of stations near the shortest path. For the examples in Table 1, the prototype returned results in 2–35 s using residential broadband. Actual performance is mainly a function of road and station density near the origin and destination. Computation time is faster for hydrogen because there are fewer stations and Hanover is in a rural area. Computation time decreases as the driving range decreases or when assuming a round trip or a starting fuel level less than 100% because it decreases the size of the Euclidean circles around the origins and destinations.

Conclusions

This paper presented an algorithm using readily available web-mapping and routing tools to find the shortest refuelable paths for AFVs given a driver's origin and destination, type of fuel, vehicle driving range, starting fuel level, and whether it's a one-way or round trip. The algorithm first generates a feasible network in matrix form in which all edges represent paths among stations and origin and destination points that can be completed given the AFV driving range. Once this network is constructed, finding the shortest *refuelable* path is as simple as solving a basic shortest path algorithm. Computation time is enhanced by preprocessing an inter-station distance matrix, which is edited by the algorithm when a user submits a query. An online prototype demonstrates that these methods can be successfully combined with web-based mapping and still solve in a time that is competitive with existing route planning tools that do not find the optimal fuel-specific, range-sensitive route or guarantee a feasible route.

Online tools such as this can benefit AFV drivers, the alternative-fuels industry, and society in general. In addition to use by AFV drivers, prospective buyers could use it to determine if a vehicle suits their driving patterns before purchasing it. Society benefits by reducing travel time, energy use, pollution, and the number of stranded motorists.

Future extensions should address practical issues that theoretically are simple to incorporate, such as the ability to handle intermediate stops, a fuel reserve for making local trips at the destination, and the effect of topography on energy consumption in different directions. For web-based implementation, the solution time can be nearly halved by issuing simultaneous queries to Google Maps® to find the driving distances from both the origin and the destination to the stations within range. For “flex-fuel” vehicles, the model could be extended to allow drivers to fill at gasoline or diesel stations under certain user-defined conditions.

REFERENCES

[1] Kim J, Lee Y, Moon I. Optimization of a hydrogen supply chain under demand uncertainty. Int J Hydrogen Energy 2008;33(18):4715–29.

[2] Parker N, Fan Y, Ogden J. From waste to hydrogen: an optimal design of energy production and distribution network. Transp Res E Log 2010;46(4):534–45.

[3] Kuby MJ, Lines L, Schultz R, Xie Z, Kim J-G, Lim S. Optimization of hydrogen stations in Florida using the flow refueling location model. Int J Hydrogen Energy 2009;34(15):6045–64.

[4] Brey JJ, Carazo AF, Brey R. Using AHP and binary integer programming to optimize the initial distribution of hydrogen infrastructures in Andalusia. Int J Hydrogen Energy 2012;37(6):5372–84.

[5] Soedarmadji E, McEliece RJ. Optimal worst-case QoS routing in constrained AWGN channel network. In: Proc IEEE Int Conf Comm; 2007. p. 153–7.

[6] Khuller S, Malekian A, Mestre J. To fill or not to fill: the gas station problem. ACM Trans Algorithms 2011;7(3).

[7] Lin SH, Gertsch N, Russell JR. A linear-time algorithm for finding optimal vehicle refueling policies. Op Res Lett 2007;35:290–6.

[8] Suzuki Y. A generic model of motor carrier fuel optimization. Nav Res Logist 2008;55:737–46.

[9] Adler JD, Mirchandani PB, Xue G, Xia M. The electric vehicle shortest-walk problem with battery exchanges. Netw Spat Econ 2014 [in press], http://dx.doi.org/10.1007/s11067-013-9221-7.

[10] Melendez M. Transitioning to a hydrogen future: learning from the alternative fuels experience. Golden, CO: National Renewable Energy Laboratory; 2006. Technical Report No. NREL/TP-540–39423.

[11] Pearre N, Kempton W, Guensler RL, Elango VV. Electric vehicles: how much range is required for a day's driving? Transp Res C Emer 2011;19:1171–84.

[12] National Renewable Energy Laboratory, Alternative Fuels Data Center. Alternative fuel station locator. Available from: www.afdc.energy.gov/locator/stations/route/ [accessed 06.06.14].

[13] CNG Trip Planner. Available from: www.cngprices.com/trip_planner.php [accessed 06.06.14].

[14] Gibgas Tankstellen. Available from: http://www.gibgas.de/Tankstellen/Umkreissuche - Routenplaner [accessed 06.06.14].

[15] Kuby M, Lim S. The flow-refueling location problem for alternative-fuel vehicles. Socio Econ Plan Sci 2005;39:125–45.

[16] Dijkstra E. A note on two problems in connexion with graphs. Numer Math 1959;1:269–71.

[17] Simchi-Levi D, Berman O. A heuristic algorithm for the traveling salesman location problem on networks. Oper Res 1988;36:478–84.

[18] Bast H, Funke S, Sanders P, Schultes D. Fast routing in road networks with transit nodes. Science 2007;316:566.

[19] Google. Geocoding service. Available from: https://developers.google.com/maps/documentation/javascript/geocoding [accessed 20.20.13].

[20] Floyd RW. Algorithm 97 shortest path. Comm ACM 1962;345(5–6).