Green Routing Fuel Saving Opportunity Assessment: A Case Study on California Large-Scale Real-World Travel Data

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Green Routing Fuel Saving Opportunity Assessment: A Case Study Using Large-Scale Real-World Travel Data

Lei Zhu, Jacob Holden, Eric Wood, and Jeffrey Gonder

Abstract—**New technologies such as connected and automated vehicles have attracted more and more research attention for their potential to improve the energy efficiency and environmental impact of current transportation systems. Green routing is one such connected vehicle strategy under which drivers receive information about the most fuel-efficient route before departing for a given destination. This paper introduces an evaluation framework for estimating the benefits of green routing based on large-scale, real-world travel data. The framework has the capability to quantify fuel savings by estimating the fuel consumption on alternate routes that could be taken between two locations and comparing these to the estimated fuel consumption of the actual route taken. A route-based fuel consumption estimation model that considers road traffic conditions, functional class, and grade is proposed and used in the framework. A study using a large-scale, high-resolution data set from the California Household Travel Survey indicates that 31% of actual routes have fuel savings potential, and among these routes the cumulative fuel savings could reach 12%. Alternately calculating the potential fuel savings relative to the full set of actual routes (including those that already follow the greenest route recommendation), the potential savings relative to the overall estimated fuel consumption would be 4.5%. Notably, two thirds of the fuel savings occur on green routes that save both fuel and time relative to the original actual routes. The remaining third would be subject to weighing the potential fuel savings against required increases in travel time for the recommended green route.**

I. Introduction

The U.S. transportation sector accounted for about 28% of energy consumption and 70% of petroleum consumption in 2014 [1]. Recently, emerging intelligent transportation system technologies such as connected and automated vehicles have attracted more and more attention because they can be implemented in the near term and can positively impact mobility, fuel consumption, and greenhouse gas emissions [2-4]. One particular interest is to provide drivers or vehicles guidance to achieve fuel-efficient driving [5]. Guiding drivers or vehicles to choose more fuel-efficient routes is referred to as "green routing" [6]. The selected route determines the road features and the traffic conditions, which are dominant factors in the resulting driving pattern and fuel efficiency. Nie and Li claimed that when the route is determined, the microscopic operational tactics seem to have relatively small influence on operating speed and fuel efficiency [7]. Therefore, if a driver knows the expected fuel consumption of all possible alternative routes before departure, following the most fuel-efficient "green route" recommendation will likely save fuel and reduce greenhouse gas emissions.

Pre-trip fuel consumption estimation methods rely on correlations between fuel consumption and various influencing factors about trips, vehicles, and drivers. Macroscopic models assume a fixed fuel consumption rate for a given vehicle or powertrain model (such as a vehicle's average fuel economy rating). Microscopic-level models, such as the Future Automotive Systems Technology Simulator (FASTSim) [8], Autonomie [9], VT-Micro [10], and the Comprehensive Modal Emissions Model (CMEM) [11], consider vehicle driving and road details and can accurately estimate fuel consumption. However, they require detailed drive cycle information [12]. Mesoscopic-level models do not need full drive cycles and consider fuel economy impact factors, such as trip road features, that offer better estimation results than the macroscopic models. The present mesoscopic-level studies [11, 13, 14] mainly rely on average trip speed to determine trip fuel consumption rate (in units of liters per 100 km or gallons per 100 miles). This study applies an enhanced pre-trip fuel consumption rate estimation model, which was trained and developed using millions of second-by-second driving trajectory data points obtained from global positioning system (GPS) data collection devices. The model considers road traffic conditions, functional class, and grade factors for a typical conventional vehicle. The advantage of the resulting fuel estimation model is that once it is trained it does not need complete second-by-second trip drive cycles and is able to provide specific fuel consumption rate estimates for any given driving route that has not yet been driven.

Routing algorithms used to support a green routing application stem from the traditional shortest path finding algorithms, such as the Dijkstra algorithm, by integrating fuel consumption cost into link cost [15]. Like other shortest path routing applications, a green routing service requires a server for addressing various routing requests. However, hosting and maintaining a routing server is costly and requires detailed and accurate real-world traffic and network data [15-20], which are difficult to collect and process.

Some studies bypass the rigorous data collection requirements by taking traffic outputs from traffic simulations, such as TRansportation ANalysis SIMulation System (TRANSIMS) or DynusT (Dynamic Urban Systems

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in Transportation) for a certain study area [21, 22]. However, the traffic simulation applications are not easy to implement and require considerable computational and data storage resources. Moreover, their link cost attributes can be relatively simplistic in the area of energy estimation. Additionally, the simulation and traffic assignment results do not reflect real-world travel conditions. Fuel-saving analysis based on simulation solutions may therefore not be accurate. It is desirable to instead find an efficient and effective way to evaluate routing alternatives in real on-road conditions.

Routing application programming interfaces (APIs), such as Google Maps Directions API [23, 24], provide feasible route solutions for any origin/destination (O/D) pairs by considering typical real-world traffic conditions. The API routes are conveniently obtained, and the routes are reliable due to the commercial maturity of the technology and its supporting high-quality road network and real-time traffic data. While the standard API route options may not capture the absolute fuel-minimal "greenest route", the options offered may reasonably be expected to represent the most logical alternatives when considering both travel time and ease of following the directions, and offer several alternatives for comparison against the actual route driven in order to quantify potential fuel savings for realistic alternative routes.

The remainder of this paper describes the proposed evaluation framework for green routing fuel-saving opportunities using a routing API and the enhanced pre-trip fuel consumption rate estimation method. The paper will also describe application of this framework to quantify fuel-saving opportunities for a large-scale, real-world travel data set by comparing the API-recommended routes to the actual route. The features of the proposed green routing fuel-saving evaluation method are:

- Using the enhanced pre-trip fuel consumption rate estimation model to calculate fuel consumption over potential routes that do not have second-by-second driving data. This enables fuel consumption estimation over routes that were not actually driven (and calculation of fuel consumption before travel in order to identify the greenest route).
- Using a large-scale, real-world travel data set (rather than either simulated or small-scale travel data) to quantify expected fuel savings from green routing. This approach provides a reliable and feasible fuel saving result based on real-world data.
- The API (e.g., Google directions API) method of providing the alternative routes is easy to implement and compatible with any cities having real travel data. The proposed framework can be implemented as a universal application tool for assessing on-road energy consumption for vehicles in any area.

II. Methodology

The green routing fuel-saving opportunity evaluation framework leverages the directions API to obtain the alternative routes for any OD pair and selects the most fuel-efficient route as the greenest route by applying pre-trip fuel economy estimation techniques Comparing the greenest route fuel-consumption predictions to the actual route taken by GPS-instrumented drivers defines the fuel-saving opportunity space. The green routing fuel-saving opportunity evaluation framework includes the steps below. The workflow is shown in Fig. 1.

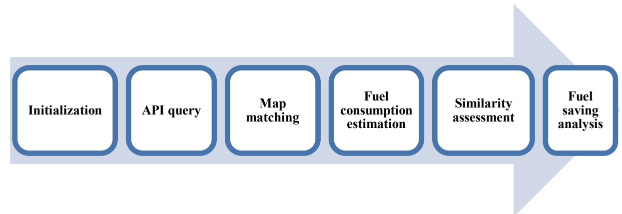

Fig. 1: Workflow of green routing fuel saving opportunity evaluation framework.

Step A: **Initialization.** Prepare actual route GPS trajectory data and extract O/D pairs.

Step B: **API query.** Query directions API and obtain API routes for each O/D pair, including route topology and traffic data.

Step C: **Map matching.** Map match API routes and actual routes to a common road network, and obtain link attributes, such as functional class and road grade.

Step D: **Fuel consumption estimation.** Estimate route-specific fuel consumption for API routes and actual routes.

Step E: **Similarity assessment.** Determine if the actual route matches one of the API routes.

Step F: **Fuel saving analysis.** Analyze fuel consumption and travel time comparisons between greenest routes and actual routes.

Several definitions and notes are listed below.

- Actual route: The actual route is the path driven by a GPS-instrumented vehicle from origin to destination. An actual route consists of a sequence of GPS points with coordinates, point speeds, and time stamps.
- API route: The directions API provided routes consist of a sequence of shape nodes. The directions API (e.g., Google directions API) provides one or more routes and navigation information, including polyline, distance, duration in traffic, and leg information, for a given OD pair.
- Greenest route: The greenest route is the most fuel-efficient route among the actual route and its corresponding API routes for a given OD pair.

A. *Initialization*

A pre-process procedure cleanses the raw GPS trajectory points and detects the actual route trajectory segments for different drivers. When the actual route trajectory segments are determined, the route origin and destination locations are extracted from the first and last trajectory point coordinates. Additionally, the trip departure time is directly read from the timestamp of the first trajectory point. The actual route point-based speed sequence (speed profile) is obtained to reflect the actual route traffic conditions. Moreover, the actual route distance is computed by summing the coordinates' point-to-point distances among all consecutive trajectory point pairs.

B. API Query

For each O/D pair, the method queries an API (e.g., Google directions API) to obtain API routes according to the O/D locations and the departure time. Since the API does not offer the route speed profile, a two-level API query method is proposed to obtain the API route topology, distance, and duration in different traffic conditions. First, the API query gets multiple consecutive route segments (legs), which are separated by the turn-points, e.g., left/right turn points. Then, the second-level API query is conducted to fetch the polyline, duration, and distance features for each route segment. After decoding the polyline string, the segment shape nodes are obtained and they compose the route topology. The average speed for each segment is calculated by the segment distance over the segment duration.

C. Map Matching

The API routes and the actual routes have very limited road network information. However, additional road network details, such as functional class and elevation profile, are critical for route fuel consumption analyses. The map-matching procedure [25–27] matches the API routes and the actual routes onto a common road network to obtain the road facility information, according to the shape nodes and GPS points for each route. After map matching, each GPS point in the actual routes or each shape node in the API routes is associated with a specific road link. The point-based sequence of road functional class (marked as "frc," which represents the road type) and elevation profile (in feet) are procured by retrieving the matched links. The functional class sequence and elevation profile are used to generate the route-level functional class and grade attributes for route-based fuel consumption estimation.

D. Fuel Consumption Estimation

With detailed road link information (link-level average speed, functional class, and road grade), an enhanced fuel consumption rate estimation model is able to determine the expected fuel consumption for a given vehicle over the route. The Future Automotive Systems Technology Simulator (FASTSim) [28] is used in conjunction with real-world driving data, made available by the Transportation Secure Data Center (TSDC) at the National Renewable Energy Laboratory [29], to obtain the FASTSim-estimated fuel economy data as the ground truth. These driving data are used as the feedstock for developing an energy estimation model that does not require second-by-second drive cycles to predict fuel economy at the trip level.

1) Fuel Consumption Rate Estimation Methodology

The TSDC hosts millions of miles of on-road driving data. Development of the pre-trip fuel consumption rate estimation methodology used in this paper relied on a subset of TSDC data consisting of roughly 150 million spatial points from real drivers acquired at a 1-Hz frequency. The U.S. Geological Survey's Digital Elevation Model together with an NREL-developed filtering routine are used to append road grade information to the drive cycle data, and the GPS points are matched to a road network with the previously described map-matching procedure.

Once the raw driving data have been cleaned and filtered, FASTSim is run for all drive cycles to determine the second-by-second fuel consumption for the drive cycle. For this work, the second-by-second FASTSim fuel consumption results from a model representative of a typical conventional sedan are taken to be the ground truth. The point-based FASTSim results are then aggregated to the link level. All points on the same link are grouped, yielding link level results that include total fuel consumption, functional class, road grade, and average speed of travel.

The link-level results are grouped into "bins" by average speed, functional class, and road grade. The average fuel consumption rate is calculated from the link-level FASTSim results for each bin, which generates the estimation model. Fig. 2 shows fuel economy against average speed for each functional class bin in the model. Fig. 3 has percentage correction factors for road grade to be applied to the quantities (converted to fuel consumption rate) in Fig. 2 The shorter curves in Fig. 3 indicate bins that did not contain a sufficient sample size (a bin must have over 500 miles of total driving data). Overall, the accuracy of the model is calculated from the modeled to ground truth error in estimated fuel consumption (gallons) for a trip. The averaged absolute error for all trips used to generate this model is approximately 7.6%.

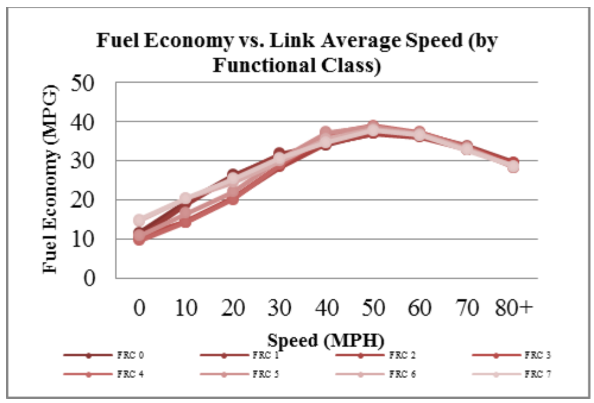

Fig. 2: Workflow of green routing fuel saving opportunity evaluation framework.

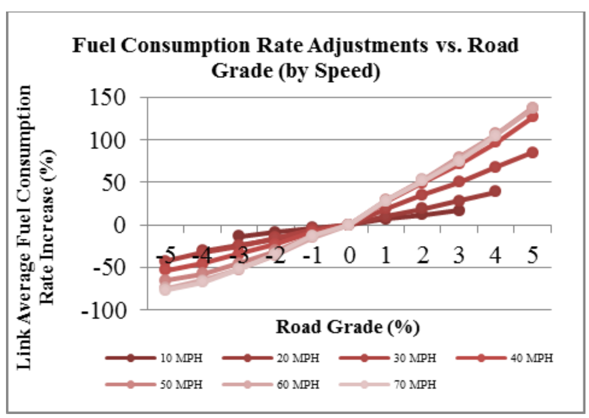

Fig. 3: Fuel consumption rate correction percentages, as a function of road grade and link average speed.

2) *Fuel Consumption Estimation Implementation*

According to the fuel consumption rate estimation model, the fuel consumption rate of a driving segment can be estimated by its average speed, functional class, and road grade. However, the model cannot be directly applied to a full driving route that contains a mixture of driving segments with different average speed, functional class and road grade values. When applying the estimation model to identified driving routes, each route is therefore first divided into smaller sub-routes that fall in the same average speed, functional class, and road grade bins.

For occasions when a divided segment is too short, meaning the segment distance is less than 0.1 mile, the short segment is merged into the preceding one. When the sub-routes are determined, the sub-routes' distances are calculated according to the sub-route node coordinates. Sub-routes are thus considered as the basic units for obtaining the fuel consumption by searching the fuel consumption rate tables. Each sub-route's fuel consumption in gallons is then computed from its distance (in miles) divided by the estimated fuel consumption rate (in mpg). Therefore, the fuel consumption for the entire route is obtained by summing the estimated fuel consumption over each of the sub-routes.

E. *Similarity Assessment*

After estimating all routes' fuel consumption the potential for fuel savings is examined—specifically by evaluating whether or not the actual route is the least fuel consuming ("greenest") route. For cases where an actual route matches one of its API routes, the fuel consumptions of the matched API route and the actual route are assumed to be the same. Therefore, before studying the fuel-saving opportunity, the relationships of actual routes and API routes need to be investigated. The similarity relationship of an actual route and an API route is described by a node-based sequence's longest common subsequence similarity score system [30][31]. According to the longest common subsequence scores, an API route is matched to the actual route when the API route similarity score is the maximum score of all API routes and is also greater than a pre-defined similarity threshold (for example, max score > threshold of 0.7). Otherwise, the actual route is flagged as not matching any of the API-recommended routes.

F. *Fuel Saving Analysis*

The fuel-saving analysis quantifies the potential fuel savings and evaluates the fuel saving and travel time relationship. In the analysis, the actual routes are first separated into two groups: "follow API" and "non-follow API," according to whether an actual route matches one of the API routes. For the "follow API" group, the estimated fuel consumption of the actual route is replaced by the estimated fuel consumption of the matched API route, and it is compared to other API routes. If the matched API route fuel consumption is greater than that of other API routes, the actual route is not the greenest route, and a fuel savings exists. In that case, the actual route is categorized as "API potential fuel saving route." Otherwise, the actual route is denoted as "API greenest route." On the other hand, for the "non-follow API" group, the fuel consumption estimates of the actual route (calculated using the same pre-trip fuel consumption estimation methodology used on the API routes) and those of the API routes are directly compared. If the actual route is not the greenest route, it is defined as "actual potential fuel-saving route." Otherwise, the actual route is taken to be the greenest route. In these cases the actual route is referred to as the "actual outperform route." Ultimately, the entire set of actual routes is divided into four groups: 1) API potential fuel saving routes, 2) API greenest routes, 3) actual potential fuel saving routes, and 4) actual outperform routes.

Determining the total fuel savings requires calculating the cumulative fuel consumption of the four groups of routes. The fuel-savings equals the fuel consumption differences of the actual routes and the greenest routes from Group 1 and Group 3.

In addition to quantifying the fuel savings opportunity it is informative to examine the relationship between the travel time impact of the identified green routes relative to the actual routes taken. This will reveal the relative time penalty that a traveler would incur to realize the predicted fuel savings (or double benefit of time and fuel savings if the green route is also expected to be faster than the actual route taken). The detailed analysis case study uses data from the 2010-2012 California Household Travel Survey which is hosted in the TSDC [29].

III. Experiment and Results Discussion

This section introduces a green routing potential fuel-saving analysis based on the aforementioned Caltrans data set hosted in the TSDC. The data set has 44,805 O/D pairs and contains 4,265,064 GPS points, which are extracted from 111,096 miles of actual driving routes in California.

The initialization pre-processes the raw GPS trajectory data and extracts actual routes, including route O/D pairs, departure time, and GPS trajectory segments. Google API then provides the API routes and their traffic information for each O/D pair. This results in a total of 100,031 API-procured routes (an average of 2.2 API route options per O/D pair). A commercial road network layer (together with the previously-described road grade derivation procedure) is used to append road link attributes to both the actual and the API-derived routes. Next, the routes' fuel consumptions are predicted by the pre-trip fuel consumption estimation approach. Meanwhile, the similarity relationships of actual routes and API routes are investigated using the similarity assessment procedure. This enables a large-scale green routing fuel savings opportunity analysis to be conducted using the Caltrans travel data.

A. *Overall Actual Route Ratio Distribution*

The actual routes are categorized into four groups. When the similarity score threshold is set at 0.7, a total of 78% of actual routes are found to follow one of the API routes. Furthermore, 58% of the actual routes match the greenest route suggestion (i.e., Group 2, API greenest route), while 20% of actual routes match the API routes but not the greenest routes (i.e., Group 1, the API potential fuel saving route). On the other hand, 22% of actual routes do not follow one of the API routes. By splitting up these "non-follow API" routes according to their fuel saving potential, 11% of actual routes are potential saving routes (i.e., Group 3, actual potential fuel saving route), and 11% of actual routes outperform all API routes in terms of fuel consumption (i.e., Group 4, Actual outperform route). The ratio distribution of the actual routes is illustrated in Fig. 4.

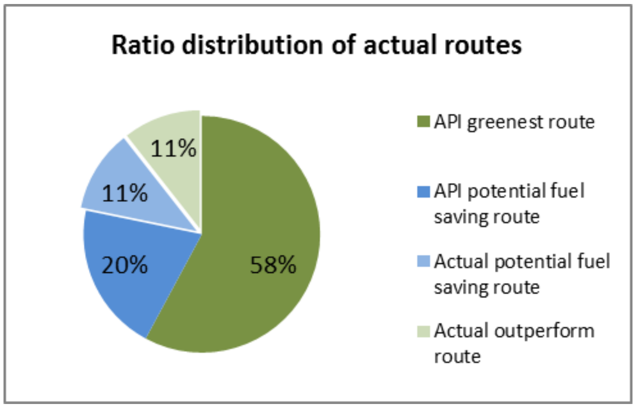

Fig. 4: Ratio distribution of actual routes.

In Fig. 4, 31% of actual routes (dark and light blue) have fuel-saving potential while 69% of actual routes (dark and light green) do not. Within the possible fuel-saving routes, a majority of them (20%) follow a "less green" API route and 11% of them follow "less green" actual routes that do not match any of the API-recommended routes. As a side note, given that an equal number of the non-API-matched routes show fuel savings versus no fuel savings potential, whereas a greater proportion of the API matched routes show no fuel savings versus fuel savings potential (58% vs. 20%) it appears that if an actual route matches one of the API routes, the actual route is more likely to be a green route.

B. *Fuel Consumption and Fuel Savings*

The cumulative fuel consumption for potential fuel-saving routes and non-fuel-saving routes are demonstrated in Fig. 5. The columns labeled as "actual" and "green" denote the actual routes and their corresponding greenest routes. The red bar in the "actual" column represents the cumulative estimated fuel consumption (3,896 gallons) of potential fuel saving actual routes, from Group 1 and Group 3. The red bar in the "green" column illustrates the cumulative fuel consumption (3,420 gallons) of the greenest routes corresponding to the potential fuel-saving actual routes. The blue bar in the "actual" column represents the cumulative fuel usage of actual routes that are already the least fuel consuming route options (6,718 gallons, which is identical with the cumulative fuel consumption of the corresponding greenest routes, marked with a matching blue bar in the "green" column).

From this analysis, the potential fuel savings by greener routes that differed from actual routes taken is 476 gallons (3,896 – 3,420 gallons), which is 12% of the cumulative fuel consumption from actual routes that showed fuel saving potential. Relative to the overall fuel consumption estimate for all of the actual routes examined (10,614 gallons), the potential 476 gallons of fuel savings equals roughly 4.5% of the total.

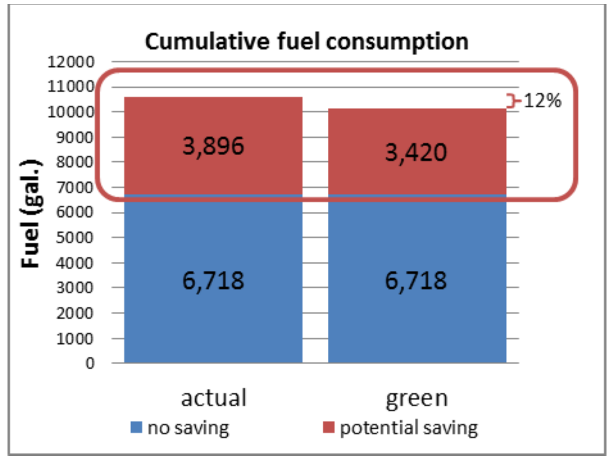

Fig. 5: Cumulative fuel consumption bar chart for actual routes compared to the least fuel consuming green route options.

C. *Trade-Offs between Fuel Savings and Travel Time*

The actual routes with fuel saving potential are the targets of this research. However, it is important to consider potential travel time impacts if those actual routes were to switch to the alternative green routes that have been identified. The green routes sometimes provide time penalties and sometimes provide time savings.

Fig. 6 shows a scatter diagram of the fuel-saving and travel-time differences between actual routes with potential for fuel savings and the corresponding greenest routes. Each dot on the figure is placed at the location on the fuel saving vs. time difference space that corresponds to the specific gallons and seconds differences between the actual and green routes. For additional reference, the actual route duration is indicated by the color, which ranges from 15 to 10,800 seconds. The actual route duration minus the greenest route duration gives the travel time difference. The actual routes with time and fuel savings are the most desirable routes (which are those located above the dashed black zero time difference line). These represent 49% of the total actual routes with fuel saving potential. The total fuel savings of this subset is 315 gallons—indicating that while this subset represents just under half of the routes with fuel saving potential it represents roughly two thirds of the total 476

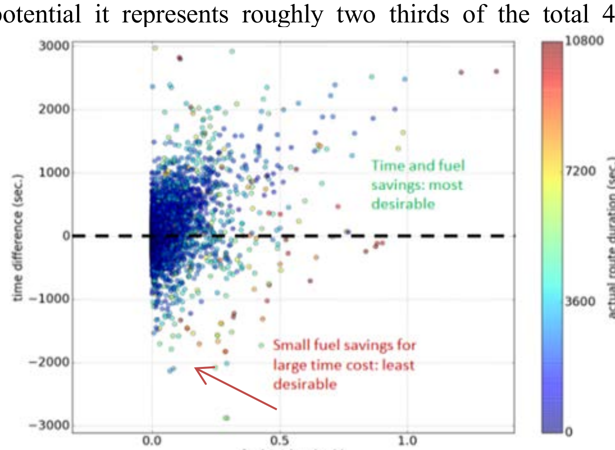

Fig. 6: Fuel saving vs. time difference for potential fuel saving actual routes

gallon fuel saving potential calculated for the entire set of routes. The cumulative time savings for this subset of most desirable green route alternatives is 438 hours, which is about 21% of total travel time of all the actual routes in this subset above the black line.

It follows that the remaining potential fuel savings (161 gallons total) for the points below the dashed line come at a cost of increased travel time (which totals 263 hours for this subset of routes). Note that a straight line drawn from the origin at zero fuel and time savings in Fig. 6 and through any point below the black line will have a slope describing the relative time cost to achieve the corresponding fuel savings for routes that fall along that line. Routes with the steepest negative slope (lying close to the negative y-axis in Fig. 6) are the least desirable as they require significant time penalties to achieve relatively little fuel savings. Routes falling along less negatively sloped tradeoff relationship lines (closer to the x-axis) would be much more desirable green route alternatives as they achieve fuel savings with relatively small increased travel time required. It is informative to consider different threshold slopes for the travel time penalty vs. fuel savings relationship in the negative region of Fig. 6, and to assume that routes falling to the clockwise side of such a line would not be worth switching to the alternative green route whereas the fuel savings for routes on the counterclockwise side would be worth the corresponding time penalty.

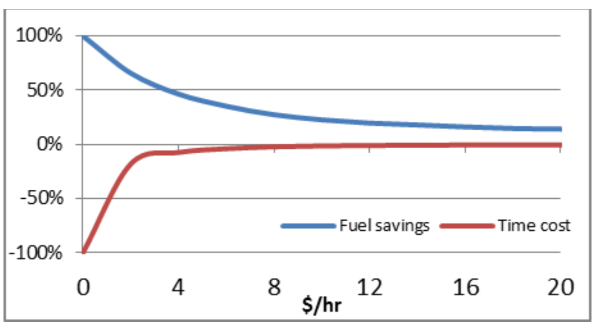

Fig. 7: Value-of-time threshold impacts on the cumulative fuel savings and time penalties for the subset of green routes that require longer travel time.

Fig. 7 shows the results from setting different threshold values and excluding green route options with a worse time vs. fuel savings tradeoff than is set by the threshold. To make the threshold values more intuitive to understand, the values for gallons saved are converted into dollars by applying an assumed fuel cost of $2.50/gallon. Following this conversion, the inverse of each threshold slope described in the previous paragraph are calculated and plotted along the x-axis of Fig. 7 in units of dollars per hour. The red and blue curves indicate the percentage of the cumulative time penalties (time cost) and fuel savings that remain for this green routing subset where fuel savings and increased travel time must be traded off.

At a threshold of $0/hour for the monetary value of any longer travel time requirements, the cumulative fuel savings and travel time increase for this subset of routes remain at 100% of the previously mentioned values (161 gallons and 263 hours, respectively). Increasing the threshold value to $2/hour reduces the cumulative fuel savings to 66% of the initial value (i.e., to roughly 106 gallons) and even more dramatically reduces the cumulative time penalty (specifically to 18% or roughly 47 hours). Further increasing the threshold to $12/hour reduces the cumulative time penalty to 1% of the original (or to roughly 2.6 hours) and brings the corresponding fuel savings opportunity for this route subset to 20% of the original (or to roughly 32 gallons). The total fuel savings opportunity over all routes for this threshold (including those for which the green route saves both time and fuel relative to the actual route, and those for which the tradeoff between reduced fueling costs and longer travel time is equal or better than $12/hour) is 315 + 32 or 347 gallons. Relative to the full 10,614 gallons estimate for the entire set of actual routes (including those that already match the greenest route recommendation), the 347 gallons green routing fuel savings opportunity works out to be 3.3%. (Recall that the comparable value had been 4.5% if no threshold is set to restrict any time penalties that accompany some of the identified green routes).

IV. Conclusions

The proposed framework for evaluating green routing fuel-savings opportunities provides a feasible way to assess potential fuel savings for a large-scale, real-world travel data set. From a sample data set with 44,805 O/D pairs, 31% of actual routes show an opportunity for fuel savings through green routing. The corresponding cumulative fuel savings estimate is 476 gallons, which is 12% of the total fuel consumption for the routes that show a potential green routing benefit, or alternately, 4.5% of the total fuel consumption for the entire set of actual routes (including those that already follow the greenest route). Notably, two thirds of the green routing savings come from routes estimated to save time as well as fuel relative to the original actual route. The remaining third of the fuel savings derives from green routes that would incur some amount of time penalty relative to the original actual route, and for at least some portion of these drivers may reasonably decide that the increased travel time requirement is not worth the fuel savings that can be achieved.

The green routing fuel-savings evaluation framework is transferable and can be developed as a application tool for any location having real-world travel data. Anticipated extensions of the current work include expanding beyond the single representative conventional vehicle model applied for the present analysis to multiple different vehicle powertrain models. In addition, work is under way to collect ground-truth on-road fuel consumption data for multiple vehicles traveling between sample O/D pairs in order to even more robustly validate the green routing estimation framework.

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