THE EFFECT OF ROAD ELEVATION ON NETWORK WIDE VEHICLE ENERGY CONSUMPTION AND ECO-ROUTING

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ABSTRACT

Due to growing concern about the impact of emissions from the transport sector on global climate change, vehicle energy consumption is a factor of great interest to network planners. In addition, drivers are interested in reducing energy consumption and thus fuel costs. However, traditional vehicle energy consumption models have neglected an important factor: change in road elevation. This assumption has traditionally been supported by the idea that the energy consumed due to gradient would be reflected in changes in speed and acceleration, but an aggregate network demonstration on a realistic sized city has been difficult to show. This work demonstrates the impact of road gradient change on network wide vehicle energy consumption by integrating energy consumption equations based on the road load equations, elevation data available from the Google API, and a dynamic traffic assignment model to capture the effect of user route choice. This work quantifies the impact of the energy consumed due to road elevation change on two city networks, and results indicate that the effects of gradient should not be excluded from vehicle energy consumption evaluations. Additionally, the effects of “eco-routing”, in which drivers choose the least energy consumed shortest path, are explored. Results on the city networks indicate that if drivers do not account for gradient, they may choose a route that actually increases vehicle energy consumption. The modeling tool proposed in this work is scalable and easily adaptable for different cities.
1. INTRODUCTION

The detrimental impact of emissions from the transport sector is an issue of growing concern for both city planners and drivers alike. From a planning perspective, infrastructure design to minimize vehicle emissions and energy consumption may have a beneficial environmental effect. Likewise, for individual drivers, minimizing vehicle energy consumption will lessen “carbon footprint” and provide the monetary benefit of reduced fuel costs. Additionally, as fuel prices rise and the environmental burden caused by pollution increases, drivers and city planners may find eco-routing, in which drivers choose routes to minimize energy consumption rather than travel time, more attractive. Furthermore, energy consumption is a proxy for mobile emissions, and thus a path minimizing energy consumption will also reduce vehicle-sourced emissions.

While vehicle energy consumption models have a rich history in both practice and the literature, the impact of road elevation change is often neglected or accounted for using changes in speed, acceleration, and braking. While this approach is practical for certain applications or in flat topology, variations in speed and acceleration on roads of different gradients may constitute a significant source of energy consumption. Consequentially, minimum energy routes calculated including gradient changes may be more accurate and result in a greater reduction of fuel consumption by eco-routing vehicles. This work seeks to demonstrate the importance of accounting for gradient when making vehicle energy consumption estimates.

Energy consumption models used with transport applications focus on an aggregate, network level, often based on instantaneous fuel consumption equations that are integrated with microscopic traffic simulation models. While microsimulation models capture a fine-grained detail of individual user behavior, they are not scalable to large city networks, and are unsuitable to evaluate network wide vehicle energy consumption and eco-routing. Therefore, this work instead utilizes a dynamic traffic assignment (DTA) tool in order to achieve an aggregate perspective on vehicle energy consumption and eco-routing strategies. DTA models time-varying flow and congestion propagation, allowing for detailed vehicle energy consumption analysis without the computational requirements of microsimulation.

This work builds upon previous vehicle energy consumption models to propose a tool for evaluating vehicle energy consumption with a DTA model that includes the effect of road gradient. To the authors’ knowledge, this is the first work to examine the impact of road elevation change on vehicle energy consumption on an aggregate city-wide level. This work demonstrates the change due to gradient for both individual vehicles and from a system perspective. Finally, this work evaluates the effect of gradients on eco-route choice by drivers, in which some proportion of drivers calculate and follow a minimum energy path. These results illustrate important system behavior for transport network planners.

A background on vehicle energy consumption modeling and eco-routing is provided in Section 2. Section 3 contains the detailed energy consumption and emissions equations, including gradients, applied in the proposed model, while Section 4 summarizes the importance characteristics regarding the DTA model. Section 5 demonstrates the results on downtown Austin, Texas and Nicosia, Cyprus city networks, and Section 6 concludes the work with a discussion of the many applications impacted by these results.

2. BACKGROUND

Vehicle energy consumption is a topic of vital importance for individuals, engineers, city planners, automotive industries and manufacturers, and even politicians. Individuals may be
concerned with rising fuel costs and minimizing carbon footprint. Transport and environmental engineers regularly perform environmental impact assessments evaluating vehicle emissions, while automotive engineers need to assess new vehicle technology. Transport planners are concerned with infrastructure design and its impact on energy consumed, as well as the impact on driver route choice, while the automotive industry needs to meet the demands of a population increasingly concerned with vehicle efficiency and minimizing environmental impact, as well as policy requirements aimed to reduce the global emissions impact from the transport sector. However, despite the great importance of energy consumption, the impact of road elevation change remains (to the authors’ knowledge) an unknown factor. Due to the long history of vehicle energy consumption models in the literature and in practice, only works judged to give context to the current work are included here.

On the level of an individual vehicle, complex and highly accurate software packages like ADVISOR (1) and Autonomie (2) account for detailed vehicle architectures and find precise estimations of vehicle energy consumption. These models are useful for performing vehicle technology assessments such as EPA fuel economy estimations. While these software packages require detailed vehicle inputs and are computationally complex and only available for a commercial fee, PAMVEC (3), a vehicle energy consumption modeling tool based on parametric analytical expressions developed from the road load equations. This model uses simple vehicle inputs, and estimates vehicle energy consumption with an error of less than 20% compared to the more computationally expensive dynamic simulation approach.

While dynamic vehicle simulation packages capture energy consumption on the individual level very accurately, their reliance on driving cycles to capture the dynamics of vehicle movement and their heavy computational requirements mean that these models cannot be used to look at aggregate energy consumption in a city network, and are therefore difficult to integrate with transport applications. Previous works have shown that a reliance on driving cycles to be unrealistic of actual driving (4).

Traditionally, highway models have assumed that vehicle energy consumption is a polynomial function of cruising speed (5). Previous studies have used an energy consumption equation of this form to evaluate the impact of demand uncertainty on infrastructure planning decisions considering alternative technologies (6, 7), while recent work expands this approach to highlight the importance of a multi-objective planning criteria (8).

However, such approaches cannot account for the additional energy requirements due to dynamic effects such as acceleration and braking (9). To address this need, researchers have developed instantaneous fuel consumption models, often based on the road load equations or a statistical approach that involves generating speed-acceleration lookup tables (10). Instantaneous energy consumption approaches are often integrated with traffic simulation tools such as VISSIM (11), PARAMICS (12), and AIMSUN (13), where they benefit from the increased realism of microsimulation models, but are difficult to scale to give a perspective on city-wide vehicle energy consumption. As previously stated, these models do not account for road elevation change.

While a number of works have noted the importance of elevation change on vehicle energy consumption (14), the authors were unable to identify any previous studies that provide a large scale, practical demonstration. However, a few works have addressed the issue of road elevation change. Hassel and Weber (15) calculate regression equations for emissions over different gradient and vehicle classes based on field data, accounting for variability in speed on steeper slopes. Park and Rakha (16) use the microsimulation software INTEGRATION to
examine the effect of road gradient changes on vehicle power consumption. The impact on power consumption is measured by the tractive force added by the elevation change. Park and Rakha (16) also demonstrate the impact of varying levels of road gradient. Additionally, Boriboonsomsin and Barth (17) compare the effects of road gradient on fuel consumption and CO₂ emissions using an analytical energy model and a real world field test. The analytical model uses a similar approach to measuring the additional power consumed by road gradient changes, the road load equations. In their analysis of speed profiles to minimize work and energy consumption, Chang and Morlok (18) present gradient resistance formulas for automobiles, trucks and buses, and trains, but provide energy results only for trains. However, the gradient resistance for automobiles that they develop is from the component of gravity parallel to the slope, which is similar to the concept incorporated here. Auer (19) incorporates the gradient resistance in an analysis of electric bus energy consumption.

Traditional approaches to modeling vehicle energy consumption do not include gradients. Bullock (20) gives reasons for disregarding gradient resistance, suggesting that gradient effects often are reflected in velocity fluctuations. However, Hassel and Weber (15) analyze gradient resistance despite acknowledging changes in velocity on gradients. Boriboonsomsin and Barth (17) further note that gradient data was rarely available for use. However, with the advent of GPS systems and databases such as Google Elevation API, such data is readily accessible today. Because of the need to perform large-scale case studies of city wide vehicle energy consumption, the results in this paper might provide evidence indicating whether the impacts of road gradients are significant enough to be more generally included.

3. VEHICLE ENERGY CONSUMPTION

3.1 Energy consumption model
Road vehicle performance equations detailing tractive effort and resistance are well-established and can be found in any introductory transportation textbook. This approach additionally incorporates a number of energy consumption sources related to the engine of a vehicle, influenced by the approach presented in the PAMVEC model (3). The energy consumption model in this approach determines instantaneous power requirements at six second intervals for all trips. For internal combustion engine vehicles (ICEVs), power regeneration is not available, so the total power required by the wheels to overcome resistance \( P_{\text{wheels}} \) is

\[
P_{\text{wheels}} = \max(0, P_{\text{aero}} + P_{\text{roll}} + P_{\text{accel}} + P_{\text{grade}})
\]

where \( P_{\text{aero}} \), \( P_{\text{roll}} \), \( P_{\text{accel}} \), and \( P_{\text{grade}} \) are the power requirements to overcome aerodynamic resistance, rolling resistance, gravitational resistance, and gravitational potential energy, respectively. These are found using the well-known road load equation; details concerning calculating average speed and acceleration as necessary for these equations are contained in Section 4.1. Note that road elevation is included only in \( P_{\text{grade}} \), found in this work as

\[
P_{\text{grade}} = m_{\text{total}} g \sin(\theta) v
\]

where \( m_{\text{total}} \) is the vehicle mass, \( g \) is the constant gravitational acceleration, \( \theta \) is the gradient angle, and \( v \) is average velocity. Additionally, a vehicle consumes energy due to loss from
inherent inefficiencies in the powertrain. Transmission and engine loss are included in this approach. Transmission energy loss depends on the transmission efficiency, $\eta_{\text{trans}}$.

$$P_{\text{drive loss}} = \frac{1-\eta_{\text{trans}}}{\eta_{\text{trans}}} (P_{\text{wheel}} + m_{\text{total}} k_m a v)$$  \hspace{1cm} (3)

The above power requirements, as well as accessory power for non-driving usage, is the demand on the engine:

$$P_{\text{engine}} = P_{\text{wheel}} + P_{\text{drive loss}} + P_{\text{accessory}}$$  \hspace{1cm} (4)

However, a vehicle also loses energy due to the engine efficiency $\eta_{\text{engine}}$. This power loss may be calculated as:

$$P_{\text{engine loss}} = \frac{1-\eta_{\text{engine}}}{\eta_{\text{engine}}} P_{\text{engine}}$$  \hspace{1cm} (5)

Total power usage by the ICEV is a sum of engine output and engine loss:

$$P_{\text{ICEV}} = P_{\text{engine}} + P_{\text{engine loss}}$$  \hspace{1cm} (6)

The total energy consumed by a vehicle is $P_{\text{ICEV}}$ calculated at six second intervals for all trips.

3.2 Vehicle parameters

Due to the wide range of characteristics in a typical city vehicle population, most aggregate modeling approaches choose a “characteristic vehicle” to represent all vehicles in a network. This is not a necessary assumption for the tool proposed in this work; however, because the focus of this paper is on demonstrating the impact of including road elevation change, not on operational-level project evaluation in which a technique that integrates network specific vehicle data would be necessary, this work uses the characteristic vehicle approach. Therefore, parameters for the Holden VY Commodore sedan (3) were used to calculate energy consumption of all vehicles. Additionally, this approach permits an accurate comparison of predicted energy consumption with the reported results from other energy consumption models, particularly the PAMVEC model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>frontal area</td>
</tr>
<tr>
<td>$C_D$</td>
<td>aerodynamic drag coefficient</td>
</tr>
<tr>
<td>$C_{RR}$</td>
<td>rolling resistance coefficient</td>
</tr>
<tr>
<td>$g$</td>
<td>gravitational acceleration</td>
</tr>
<tr>
<td>$m_{\text{total}}$</td>
<td>vehicle mass</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density of air</td>
</tr>
<tr>
<td>$\eta_{\text{engine}}$</td>
<td>Engine efficiency</td>
</tr>
<tr>
<td>$\eta_{\text{trans}}$</td>
<td>Transmission efficiency</td>
</tr>
<tr>
<td>$P_{\text{accessory}}$</td>
<td>Accessory power</td>
</tr>
<tr>
<td>$k_m$</td>
<td>Rotational inertia factor</td>
</tr>
</tbody>
</table>
3.3 Eco-routing
An eco-routing vehicle chooses an eco-path based on a minimum energy consumed shortest cost route. The user achieves this using an on-board GPS routing device which computes the minimum energy path based on network conditions at departure time. This approach allows for the use of time-invariant shortest path algorithms (i.e., Dijkstra’s algorithm). Future methods could be based on access to online or historic data and might result in more optimal routing, but the algorithms involved can become much more complex.

This work focuses on the application of eco-routing, and demonstrates the importance of accounting for the energy consumed due to road elevation change, lest the incorrect eco-path be chosen. However, there are several limiting assumptions to this approach, resulting from the lack of an equilibrium adjustment to eco-routing behavior. To draw an analogy with user equilibrium algorithms, if all vehicles choose the free flow shortest paths, due to congestion other paths are likely to have lower travel times. Similarly, many vehicles choosing the same eco-path could decrease speeds sufficiently to make another path require less energy. A complicating factor is the assumption that while some proportion of drivers may choose to minimize energy consumption, others might prefer to minimize travel times. A multiple vehicle class equilibrium could address this issue. However, since the focus of this paper is the impact of including gradient power requirements, a more complex equilibrium is left for future work. An evaluation of eco-routing illustrates important characteristics of system behavior, despite not including an equilibrium adjustment, and results for both the eco-routing scenario and the traditional user-equilibrium (i.e., minimum time routing) scenario are included.

4. DYNAMIC TRAFFIC ASSIGNMENT MODEL
Dynamic traffic assignment models identify network flow patterns for a specified period of time based on forecasted travel demand. One primary advantage that DTA provides over microsimulation is the ability to both model and identify vehicle routes in a large city network, and furthermore, capture the effects of route choice and traffic interaction. Realistic route modeling on large networks will significantly impact total energy consumption estimations, and alternative methods dependent on driving cycles or a microsimulation of a subnetwork will not be able to capture this effect. Additionally, network size affects the number of alternate paths available for eco-routing.

4.1 Calculating acceleration in dynamic traffic assignment
The tool proposed in this work determines vehicle trajectories using the cell transmission model (CTM) (21, 22) -based dynamic traffic assignment simulator, VISTA (23). Flow was discretized and individual vehicles were tracked at each intersection, allowing the use of energy consumption equations for individual vehicles. As a first order model CTM yields link travel times per vehicle, not acceleration. This information can be used to find the average speed experienced by a vehicle on a link; however, a link-level aggregation would not capture speed changes within a link. Therefore a method was developed to approximate within link speed changes based on at upstream and downstream ends of a link. The average speed of a link at every time step of $\Delta t = 6$ seconds was calculated using the average speed of individual vehicles on the link during that time step. Thus, the average speed of a link will change during every time step as vehicles enter and exit from a link. Acceleration was calculated as the change in average speed on a link and the average speed between links at intersections.
Formally, let \( \pi_i \) be the path of vehicle \( i \). For every link \( e \in \pi \), let \( L_e \) be the length of \( e \), \( \theta_e \) be the gradient angle of \( e \), \( \tau^i_1(e) \) be the time \( i \) arrives on \( e \), and \( \tau^i_1(e) \) be the time \( i \) exits \( e \). Then vehicle \( i \) has an average speed on \( e \), \( v^i_e \), of

\[
v^i_e = \frac{L_e}{\tau^i_1(e)-\tau^i_1(e)}
\]  

The average link speed at some time \( t \) is a function of the average individual vehicle speeds of vehicles on the link at \( t \). First define the set \( S_e(t) \) of vehicles on the link at \( t \):

\[
S_e(t) = \{i | e \in \pi_i \land \tau^i_1(e) \leq t \leq \tau^i_1(e)\}
\]  

Then the average link speed at \( t \), \( \bar{v}_e(t) \), is the average of the individual vehicle speeds of vehicles in \( S_e(t) \):

\[
\bar{v}_e(t) = \frac{\sum_{i \in S} v^i_e}{|S|}
\]  

Energy consumption for vehicle \( i \) was calculated as:

\[
\sum_{e \in \pi_i} \left[ \sum_{j=\tau^i_1(e)/\Delta t}^{\tau^i_1(e)/\Delta t-1} P \left( \bar{v}_e(j), \frac{\bar{v}_e(j+1)\Delta t - \bar{v}_e(j)\Delta t}{\Delta t}, \theta_e \right) \Delta t \right] + \left[ P \left( \bar{v}_e(\tau^i_1(e) - \Delta t), \frac{\bar{v}_{e+1}(\tau^i_1(e)) - \bar{v}_e(\tau^i_1(e) - \Delta t)}{\Delta t}, \theta_e \right) \Delta t \right]
\]  

where \( P_{ICEV}(v, a, \theta) \) is ICEV power consumption for a speed of \( v \), an acceleration of \( a \), and a gradient angle of \( \theta \), defined by equations (1) through (6), and \( e + 1 \) is the link after \( e \) on \( \pi_i \). This model assumes that in the last time step spent on \( e \), vehicle \( i \) accelerates to \( \bar{v}_{e+1}(\tau^i_1(e)) \). Further work on the realism of this assumption of acceleration will be the subject of future work.

5. DEMONSTRATION AND DISCUSSION
This section begins by demonstrating the importance of including road elevation change in aggregate vehicle energy consumption models using a small example network. The impact of road elevation change is then demonstrated on more realistic sized networks of downtown Austin, Texas, USA and Nicosia, Cyprus, and the effect on eco-route choice is investigated.

5.1 Example network
Road elevation represents an important source of energy consumption for vehicles, particularly in locations with large changes in gradient. In addition, when users base their route choice decision on the energy consumed on a particular path, their behavior may change when road elevation change is accounted for.

Figure 1 shows the demonstration network, and Table 2 contains the network parameters. The two paths from A to B are links \( \{1,2\} \) and links \( \{3,4\} \). Acceleration is zero, and net elevation change is also 0. When elevation is not considered, the least energy cost path is \( \{3,4\} \). However, when accounting for gradients, the energy to traverse links 1 and 4 is greatly reduced
(but not negative because of lack of ICEV regeneration) whereas energy to traverse links 2 and 3 is increased. The path \{1,\!2\} includes a longer downhill slope, followed by a short positive gradient, which results in a small reduction of energy. Path \{3,\!4\} travels slightly uphill, and then more steeply downhill for a shorter distance, which results in an energy consumption increase. When the topology of the demonstration network is considered, the shortest energy path becomes \{1,\!2\}. Thus an eco-routing vehicle that did not account for account for gradients actually experienced an \textit{increase} in overall energy consumption, despite behavior choices intended to achieve the opposite.

![Diagram](image)

**FIGURE 1** Demonstration network.

**TABLE 2** Results for the demonstration network.

<table>
<thead>
<tr>
<th>Link</th>
<th>Length</th>
<th>Speed</th>
<th>Travel time</th>
<th>Elevation</th>
<th>Gradient</th>
<th>Energy w/o gradients</th>
<th>Energy w/ gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3 km</td>
<td>77 km/hr</td>
<td>140 sec</td>
<td>-0.1 km</td>
<td>-1.91 deg</td>
<td>4009.4 W·hr</td>
<td>270.9 W·hr</td>
</tr>
<tr>
<td>2</td>
<td>1 km</td>
<td>77 km/hr</td>
<td>47 sec</td>
<td>0.1 km</td>
<td>5.71 deg</td>
<td>1336.5 W·hr</td>
<td>5102.9 W·hr</td>
</tr>
<tr>
<td>3</td>
<td>3 km</td>
<td>60 km/hr</td>
<td>180 sec</td>
<td>0.1 km</td>
<td>1.91 deg</td>
<td>3063.7 W·hr</td>
<td>6846.8 W·hr</td>
</tr>
<tr>
<td>4</td>
<td>1 km</td>
<td>60 km/hr</td>
<td>60 sec</td>
<td>-0.1 km</td>
<td>-5.71 deg</td>
<td>1021.2 W·hr</td>
<td>115.9 W·hr</td>
</tr>
</tbody>
</table>

**5.2 City networks demonstration**

Energy consumption calculated with and without including gradients was considered on two city networks of moderate elevation topology. The downtown Austin, Texas, USA network has 171 zones, 546 intersections, 1247 links, 62836 trips, and an average absolute gradient of 0.95 degrees. The Nicosia, Cyprus network has 702 zones, 13456 intersections, 22741 links, 58678 trips, and an average absolute gradient of 0.80 degrees. Both networks were generated from city planning data. While the topology is not flat, there are many cities with greater changes in elevation which may give more exaggerated results.

To find link gradients, Google elevation API was used to determine the elevation at each node. Link gradients were assumed constant based on the source and destination nodes. For an average link length of 0.014 km and a total link distance of 175.3 km in downtown Austin, and an average length of 0.14 km and a total link distance of 3244.6 km in Nicosia, this precision is sufficient to demonstrate the effect of gradients on energy consumption.

<table>
<thead>
<tr>
<th>Path</th>
<th>Links</th>
<th>Energy w/o gradients</th>
<th>Energy w/ gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>{1,!2}</td>
<td>5345.9 W·hr</td>
<td>5373.8 W·hr</td>
</tr>
<tr>
<td>2</td>
<td>{3,!4}</td>
<td>4084.9 W·hr</td>
<td>6962.7 W·hr</td>
</tr>
<tr>
<td>Difference</td>
<td></td>
<td>1260.9 W·hr</td>
<td>-1588.9 W·hr</td>
</tr>
</tbody>
</table>
5.2.1 Energy model verification
While the focus of this work is on the change in vehicle energy consumption due to the added consideration of gradient, not a prediction of aggregate energy consumption, an effort was made to ensure that absolute vehicle energy consumption results were not unreasonable. Using the average energy content of gasoline, the approach presented here resulted in a fuel efficiency of 9.99 km/L for the characteristic vehicle on the downtown Austin network and 12.2 km/L on the Nicosia network. The difference is only 10.9% for Austin, and 35.4% for Nicosia, compared to the reported fuel efficiency of 9.01 km/L (3). This difference may be due to specific network characteristics or the assumptions made to calculate acceleration in the DTA model.

5.2.2. City network results
Figure 2 displays the average change in energy consumption due to the inclusion of gradient for all vehicles on the downtown Austin and Nicosia networks. The horizontal axis shows average weighted path gradient, which is the average of all the link gradients on the vehicle’s path weighted by link length. A negative average path gradient indicates that the path was more downhill in nature, while a positive average path gradient indicates a path that is overall uphill. The vertical axis of Figure 2 shows the change in vehicle energy consumption due to the inclusion of gradient in the energy consumption calculations.
FIGURE 2  Energy change for individual due to including the impact of link gradient for the downtown Austin and Nicosia networks.

(a) Results from the downtown Austin network with 100% of the demand

(b) Results from the Nicosia network with 100% demand

The results show a number of observations regarding non-intuitive network behavior. While on average, a negative path gradient resulted in a decrease in vehicle energy consumption and a positive path gradient resulted in an increase in vehicle energy consumption, this was not necessarily the case. This may be the result of complex interactions between traffic and gradient energy consumption, a result that it would be difficult to capture without the use of mesoscopic traffic models such as VISTA. Moreover, in neither network does the histogram displayed in Figure 2 appear symmetric. These two observations indicate that at both the individual vehicle level and on an aggregate scale, considering road elevation will change the results of energy
consumption models. Additionally, it is not intuitive whether an estimate not including gradient will overestimate or underestimate vehicle energy consumption. In downtown Austin, not including gradients resulted in a decrease in predicted total energy consumption of 10.5%, whereas in Nicosia the decrease was 3.6%.

5.3 Impact on eco-routing
This section demonstrates the impact of including gradients when computing least energy cost paths. An eco-routing experiment was performed where the minimum energy eco-paths for between 5% - 30% of all vehicles were found for the 100% demand cases in downtown Austin and Nicosia. In the first stage of the experiment, minimum eco-paths in the DTA network state are identified by considering and not considering gradients. This represents the eco-path that the in-vehicle routing device identifies as consuming the minimum amount of energy, calculated using link energy costs at vehicle departure, where the link energy costs are updated every 15 minutes. In the second stage, a percentage of vehicles were moved to their eco-path, and the new vehicle energy consumption was computed using gradients. The second stage represents the actual energy cost experienced by the vehicle, which would include the effect of gradient. This eco-routing experiment demonstrates the impact of either accounting for gradient, or not accounting for gradient, in identifying an eco-path.

Figure 3 shows the results from the eco-routing experiment, where the horizontal axis represents the percentage of vehicles that have chosen to eco-route, and the vertical axis shows the average change in energy consumption due to re-routing per vehicle. In both networks, results demonstrate that the average energy consumption for eco-routed vehicles was consistently less when gradients were included in the eco-path identification stage. These results are not unexpected, because not accounting for gradient when choosing an eco-path means that the wrong path could be identified. However, these results further demonstrate the importance of including gradient in eco-routing, or the energy consumed on a route may actually be unintentionally increased.
FIGURE 3 Results showing the change in energy consumption per vehicle for varying percentages of eco-routing drivers.

Additionally, Figure 3 shows that for greater percentages of eco-routing drivers, the energy consumed actually increases. This point happens at a higher percentage when drivers consider gradient in their eco-route choice (~17% for Austin and ~14% for Nicosia). This is because the eco-paths became more congested due to the additional vehicles, and equilibrium effects were
not included, so vehicles did not change paths due to the congestion or additional energy consumption. While this is not perfectly representative of real eco-routing behavior, there are still two possible conclusions to be drawn from these results:

1) Not including gradient when identifying eco-paths can result in the misidentification of an eco-path and therefore overestimation of energy savings, or even an increase in energy consumption;

2) Empirical results suggest that a greater percentage of trips can be re-routed before an energy increase occurs when considering gradient. After this point, eco-paths calculated based on historical data would also lead to an energy increase, thereby suggesting a need for more complex path routing algorithms. This point occurs with a lower percentage of eco-routing drivers who don’t account for gradient.

6. CONCLUSIONS

Vehicle energy consumption is an important reflection of vehicle performance, and additionally a relevant concern in evaluating the impact of traffic policies and project evaluations, including infrastructure design and ITS technologies. This work demonstrated the importance of accounting for road elevation change in transport vehicle energy consumption models, focusing on the applications of eco-routing and network wide vehicle energy consumption.

A novel approach integrating the road load equations and the DTA tool VISTA used the downtown Austin, Texas network and the Nicosia, Cyprus network to show that individual vehicle energy consumption can vary significantly, even in networks with relatively flat topology. Results from the two networks also indicated that the network wide change in energy consumption due to road elevation is not symmetric in nature, nor is it intuitive based on the average path gradient whether individual vehicle energy consumption will increase or decrease. It may be predicted that networks with greater variation in road elevation will show even more exaggerated results.

Additionally, the exploration of eco-routing, where drivers choose the least energy consumed shortest path, demonstrated that not accounting for gradient in eco-path identification can actually lead to an increase in vehicle energy consumption. Finally, if road gradient is not accounted for, incorrect eco-routes may be chosen, and again, energy consumption may actually increase. While this work focuses on the applications of eco-routing and network vehicle energy consumption, similar miscalculations from not including road elevation may result in other applications of vehicle energy consumption models.

The current work introduced the impact of road elevation change on energy consumption by focusing on the light duty vehicle fleet, but future work will expand the current tool to include alternate vehicle technologies. Because of the flexible underlying framework of the DTA model, a multi-class expansion of the current model could help network planners make more realistic evaluations of energy consumption in a city. Other vehicle types besides passenger cars may experience more significant differences in energy consumption prediction. For instance, heavy vehicles, which typically accelerate more slowly, may require a greater proportion of cruise energy consumption to travel uphill. Many electric vehicle drivers must be conscious of range limitations, and more accurate energy consumption predictions when using gradients might assist with range anxiety. Another potential topic of interest will be in focusing on the differences in energy consumption for alternative technologies, particularly electric vehicles. It is especially important to account for elevation change when modeling energy consumption of electric vehicles due to the added effect of regenerative braking.
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REFERENCES


