Effect of Road Grade on Networkwide Vehicle Energy Consumption and Ecorouting

Michael W. Levin, Melissa Duell, and S. Travis Waller

Because of 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 models of vehicle energy consumption have neglected an important factor: road grade. This assumption has traditionally been supported by the idea that the energy consumed because of the road grade would be reflected in changes in speed and acceleration, but a demonstration of this on an aggregate network in a city of a realistic size has been difficult to show. This work demonstrated the impact of road grade on networkwide vehicle energy consumption by the integration of energy consumption equations based on road load equations, elevation data available from the Google Elevation advanced programming interface, and a dynamic traffic assignment model to capture the effect of user route choice. This work quantified the impact of the energy consumed because of road grades on two city networks, and the results indicate that the effects of grades should not be excluded from evaluations of vehicle energy consumption. In addition, the effects of ecorouting, in which drivers choose the shortest path that consumes the least amount of energy, were explored. The results for the city networks indicate that if drivers do not account for grades, they might choose a route that actually increases vehicle energy consumption. The proposed modeling tool is scalable and easily adaptable to different cities.

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, design of the infrastructure to minimize vehicle emissions and energy consumption may have beneficial environmental effects. Likewise, for individual drivers, minimization of vehicle energy consumption will lessen the individual's carbon footprint and provide the monetary benefit of reduced fuel costs. In addition, as fuel prices rise and the environmental burden caused by pollution increases, drivers and city planners may find ecorouting, 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, selection of a path that minimizes energy consumption instead of travel time (an ecopath) will also reduce emissions from vehicles.

Although models of vehicle energy consumption have a rich history both in practice and in the literature, the impact of a change in the road elevation is often neglected or accounted for through the use of changes in speed, acceleration, and braking. This approach is practical for certain applications or in flat topology; however, variations in speed and acceleration on roads of different grades may constitute a significant source of energy consumption. As a consequence, for the determination of routes that require a minimum amount of energy (referred to here as minimum-energy routes), calculations that include grade changes may be more accurate and result in a greater reduction of fuel consumption. This work seeks to demonstrate the importance of accounting for grade when vehicle energy consumption estimates are made.

Energy consumption models used with transport applications focus on an aggregate network level in which fuel consumption is often based on instantaneous fuel consumption equations that are integrated with microscopic traffic simulation models. Although microsimulation models capture individual user behavior at a high level of detail, they are not scalable to large city networks and are unsuitable for the evaluation of networkwide vehicle energy consumption and ecorouting. Therefore, this work instead uses a dynamic traffic assignment (DTA) tool to achieve an aggregate perspective on vehicle energy consumption and ecorouting strategies. DTA models time-varying flow and congestion propagation, which allows a detailed analysis of vehicle energy consumption without the computational requirements of microsimulation.

The method presented here builds on previous vehicle energy consumption models to propose a tool for evaluating vehicle energy consumption with a DTA model that includes the effect of road grade. To the authors' knowledge, this is the first work to examine the impact of a change in road elevation on vehicle energy consumption on an aggregate citywide level. The results demonstrate the change in energy consumption due to grade both for individual vehicles and from a systemwide perspective. Finally, this work evaluates the effect of grade on ecoroute choice by drivers in which some proportion of drivers calculates and follows a minimum-energy path. The results illustrate an important behavior of systems for transport network planners.

A background on the modeling of vehicle energy consumption and ecorouting is provided in the next section. The detailed energy consumption and emissions equations, including equations that take into account grades, applied in the proposed model are then provided. The important characteristics of the DTA model are summarized, and the results for the networks in downtown Austin, Texas, and Nicosia, Cyprus, are demonstrated. The work concludes with a discussion of the many applications affected by the results.

M. W. Levin, Department of Civil, Architectural, and Environmental Engineering, University of Texas at Austin, Ernest Cockrell, Jr., Hall (ECJ) 6.2, 1 University Station C1761, Austin, TX 78712. M. Duell, School of Civil and Environmental Engineering, and S. T. Waller, Research Centre for Integrated Transportation Innovation, CE110 School of Civil Engineering, University of New South Wales, Sydney, New South Wales 2052, Australia. Corresponding author: M. W. Levin, michaellevin@utexas.edu.

Transportation Research Record: Journal of the Transportation Research Board, No. 2427, Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 26–33.
DOI: 10.3141/2427-03

BACKGROUND

Vehicle energy consumption is a topic of vital importance for individuals, engineers, city planners, automotive industries, vehicle manufacturers, and even politicians. Individuals may be concerned with rising fuel costs and minimizing their carbon footprint. Transport and environmental engineers regularly perform environmental impact assessments evaluating vehicle emissions, and automotive engineers need to assess new vehicle technologies. Transport planners are concerned with the design of the infrastructure and its impact on the amount of energy consumed, as well as the impact on driver route choice; and the automotive industry needs to meet the demands of a population increasingly concerned with vehicle efficiency and minimizing the impact of their vehicles on the environment, as well as policy requirements that aim to reduce the impact of global emissions from the transport sector.

However, despite the great importance of energy consumption, to the authors' knowledge, the impact of changes in road elevation remains unknown. Because many vehicle energy consumption models have been described in the literature and their long history of use in practice, only work judged to give context to the current work is described 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 estimates of the energy consumption of vehicles. These models are useful for performing vehicle technology assessments, such as determination of U.S. Environmental Protection Agency fuel economy estimates. Whereas these software packages require detailed inputs on vehicle characteristics, are computationally complex, and are available only for a commercial fee, PAMVEC is a tool for modeling vehicle energy consumption on the basis of parametric analytical expressions developed from road load equations (*3*). This model uses simple inputs of on-vehicle characteristics and estimates vehicle energy consumption with an error of less than 20% compared with the results of the more computationally expensive dynamic simulation approach.

Although dynamic vehicle simulation packages accurately capture energy consumption on the individual level, 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 on a city network and are therefore difficult to integrate with transport applications. Previous work has shown that a reliance on driving cycles provides unrealistic energy consumption under real-world driving conditions (*4*).

Highway models have traditionally 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 decisions about infrastructure planning that consider alternative technologies (*6, 7*). Recent work has expanded this approach to highlight the importance of the use of multiobjective planning criteria (*8*).

However, such approaches cannot account for the additional energy requirements caused by dynamic effects, such as acceleration and braking (*9*). To address this need, researchers have developed instantaneous fuel consumption models, which are often based on road load equations or a statistical approach that involves the generation of 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*), in which they benefit from the increased realism of microsimulation models, but they are difficult to scale to give a perspective on citywide vehicle energy consumption. Furthermore, as stated above, these models do not account for changes in road elevation.

Although a number of studies have noted the importance of changes in elevation on vehicle energy consumption (*14*), the authors were unable to identify any previous studies that provided a large-scale, practical demonstration. However, a few studies have addressed the issue of changes in road elevation. Hassel and Weber calculated regression equations for emissions over different grade and vehicle classes on the basis of field data and accounted for variability in speed on steeper slopes (*15*). Park and Rakha used the microsimulation software INTEGRATION to examine the effect of changes in road grade on vehicle power consumption (*16*). The impact on power consumption was measured by addition of the tractive force to the change in elevation. Park and Rakha also demonstrated the impact of various road grades (*16*).

Boriboonsomsin and Barth compared the effects of road grade on fuel consumption and carbon dioxide emissions by using an analytical energy model and a real-world field test (*17*). To measure the additional power consumed by road grade changes, the analytical model used an approach similar to that used for the road load equations. In their analysis of speed profiles to minimize work and energy consumption, Chang and Morlok presented grade resistance formulas for automobiles, trucks and buses, and trains but provided energy results only for trains (*18*). However, the grade resistance for automobiles that they developed was from the component of gravity parallel to the slope, which is similar to the concept incorporated here. Auer incorporated the grade resistance in an analysis of the energy consumption of electric buses (*19*).

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

VEHICLE ENERGY CONSUMPTION

Energy Consumption Model

Equations for vehicle performance on roads detailing tractive effort and resistance are well established and can be found in any introductory transportation textbook. The approach used here additionally incorporates a number of sources of energy consumption related to the engine of a vehicle and influenced by the approach presented in the PAMVEC model (*3*). The energy consumption model in this approach determines the instantaneous power requirements at 6-s 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_{wheel}) is

$$P_{\text{wheel}} = \max\left(0, P_{\text{aero}} + P_{\text{roll}} + P_{\text{accel}} + P_{\text{grade}}\right) \tag{1}$$

where P_{aero}, P_{roll}, P_{accel}, and P_{grade} are the power required to overcome aerodynamic resistance, the power required to overcome rolling resistance, the power required to overcome gravitational resistance, and the power required to overcome gravitational potential energy, respectively. These are found by the use of the well-known road load equation; details concerning the calculation of average speed and acceleration, which are necessary for these equations, are provided below. Road elevation is included only in P_{grade}, which is found in this work as

$$P_{grade} = m_{total} g \sin(\theta) v \tag{2}$$

where

m_{total} = vehicle mass,
g = constant gravitational acceleration,
θ = grade angle, and
v = average velocity.

In addition, a vehicle consumes energy because of loss from inherent inefficiencies in the power train. Transmission and engine loss are included in this approach. Transmission energy loss ($P_{drive\,loss}$) depends on the transmission efficiency, η_{trans}:

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

where k_m is the rotational inertia factor and a is acceleration. The power requirements described earlier, as well as accessory power for nondriving use ($P_{accessory}$), are the demand on the engine (P_{engine}):

$$P_{engine} = P_{wheel} + P_{drive\ loss} + P_{accessory} \tag{4}$$

However, a vehicle also loses energy because of engine efficiency, η_{engine}. This power loss ($P_{engine\ loss}$) may be calculated as

$$P_{engine\ loss} = \frac{1-\eta_{engine}}{\eta_{engine}} P_{engine} \tag{5}$$

Total power usage by the ICEV(P_{ICEV}) is a sum of engine output and engine loss:

$$P_{ICEV} = P_{engine} + P_{engine\ loss} \tag{6}$$

The total energy consumed by a vehicle is P_{ICEV}, which is calculated at 6-s intervals for all trips.

Vehicle Parameters

Because of the wide range of characteristics in the vehicle population of a typical city, 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 demonstration of the impact of changes in road elevation and not on operation-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 a Holden VY Commodore sedan (*3*), listed in Table 1, were used to calculate the energy consumption of all vehicles. This approach also permits accurate comparison of the predicted energy consumption with the results reported from other energy consumption models, particularly the PAMVEC model.

TABLE 1 Parameters for Holden VY Commodore Sedan Used in Model

Parameter	Definition	Value
A	Frontal area	2.5 m^2
C_D	Aerodynamic drag coefficient	0.32
C_{RR}	Rolling resistance coefficient	0.01
g	Gravitational acceleration	9.81 m/s^2
m_{total}	Vehicle mass	1,640 kg
ρ	Density of air	1.2 kg/m^3
η_{engine}	Engine efficiency	0.17
η_{trans}	Transmission efficiency	0.90
$P_{accessory}$	Accessory power	1 kW
k_m	Rotational inertia factor	1.1

Ecorouting

A driver chooses an ecoroute on the basis of the minimum amount of energy that will be consumed. The user achieves this by using an onboard GPS routing device that computes the minimum–energy path on the basis of the network conditions at the departure time. This approach allows the use of time-invariant shortest-path algorithms (i.e., Dijkstra's algorithm). Future methods could be based on access to online or historical data and might result in more optimal routing, but the algorithms involved can become much more complex.

This work focuses on the application of ecorouting and demonstrates the importance of accounting for the energy consumed because of changes in road elevation, lest the incorrect ecopath be chosen. However, this approach has several limiting assumptions resulting from the lack of an equilibrium adjustment to ecorouting behavior. As an analogy with user equilibrium algorithms, if all vehicles choose the free-flow shortest paths, other paths are likely to have shorter travel times because of congestion on the free-flow shortest paths. Similarly, many drivers choosing the same ecopath could decrease speeds sufficiently to make another path require less energy.

A complicating factor is the assumption that although 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 the inclusion of power requirements for grades, a more complex equilibrium is left for future work.

An evaluation of ecorouting illustrates important characteristics of the behavior of a system, despite the lack of inclusion of an equilibrium adjustment, and results for both the ecorouting scenario and the traditional user equilibrium scenario (i.e., routing according to the route requiring the least amount of time) are included.

DYNAMIC TRAFFIC ASSIGNMENT MODEL

DTA models identify network flow patterns for a specified period of time on the basis of the 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 significantly affects estimates of total energy consumption, and alternative methods dependent on driving cycles or a microsimulation of a subnetwork are not able to capture these effects. In addition, network size affects the number of alternative paths available for ecorouting.

The tool proposed in this work determines vehicle trajectories by using the DTA simulator VISTA (*21*), which is based on the cell transmission model (*22, 23*). Flow was discretized, and individual vehicles were tracked at each intersection, which allowed the use of energy consumption equations for individual vehicles. As a first-order model, the cell transmission model yields the link travel times per vehicle and not by 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 the upstream and downstream ends of a link. The average speed of a link at every time step of 6 s was calculated by use of the average speed of individual vehicles on the link during that time step. Thus, the average speed of a link changes during every time step as vehicles enter and exit a link. Acceleration was calculated as the change in average speed on a link and the average speed between links at intersections.

Formally, let π_i be the path of vehicle i. For every link $e \in \pi$, let L_e be the length of e, θ_e be the grade angle of e, $\tau_i^{\uparrow}(e)$ be the time that vehicle i arrives on link e, and $\tau_i^{\downarrow}(e)$ be the time that vehicle i exits link e. Then, vehicle i has an average speed on link e, v_e^i, of

$$v_e^i = \frac{L_e}{\tau_i^{\downarrow}(e) - \tau_i^{\uparrow}(e)} \tag{7}$$

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

$$S_e(t) = \left\{ i \middle| e \in \pi_i \wedge \tau_i^{\uparrow}(e) \le t \le \tau_i^{\downarrow}(e) \right\} \tag{8}$$

Then, the average link speed at t, $\overline{v_e}(t)$, is the average of the individual vehicle speeds of vehicles in $S_e(t)$:

$$\overline{v_e}(t) = \frac{\sum_{i \in S} v_e^i}{|S|} \tag{9}$$

Energy consumption for vehicle i was calculated as

$$\sum_{e \in \pi_i} \left[\left[\sum_{j = \frac{\tau_i^{\uparrow}(e)}{\Delta t}}^{\frac{\tau_i^{\downarrow}(e)}{\Delta t} - 1} P_{\text{ICEV}} \left(\overline{v_e}(j\Delta t), \frac{\overline{v_e}\left((j+1)\Delta t\right) - \overline{v_e}(j\Delta t)}{\Delta t}, \theta_e \right) \Delta t \right] + P_{\text{ICEV}} \left(\overline{v_e}\left(\tau_i^{\downarrow}(e) - \Delta t\right), \frac{\overline{v_{e+1}}\left(\tau_i^{\downarrow}(e)\right) - \overline{v_e}\left(\tau_i^{\downarrow}(e) - \Delta t\right)}{\Delta t}, \theta_e \right) \Delta t \right] \tag{10}$$

where

$P_{\text{ICEV}}(v, a, \theta)$ = power consumption of ICEV for speed of v, acceleration of a, and grade angle of θ, defined by Equations 1 through 6;
$e + 1$ = link after link e on π_i;
Δt = cell transmission model timestep length; and
j = cell transmission model timestep index.

This model assumes that in the last time step spent on link e, vehicle i accelerates to $\overline{v_{e+1}}(\tau_i^{\downarrow}(e))$. The realism of this assumption for acceleration will be the subject of future work.

DEMONSTRATION AND DISCUSSION OF RESULTS

This section begins with a demonstration of the importance of inclusion of changes in road elevation in models of aggregate vehicle energy consumption by use of a small example network. The impact of changes in road elevation is then demonstrated on networks of a more realistic size by use of the networks in downtown Austin, Texas, and Nicosia, Cyprus, and the effect on ecoroute choice is investigated.

Example Network

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

Figure 1 shows the demonstration network. Table 2 contains the network parameters, and Table 3 indicates the energy consumed on each path. The two paths from Point A to Point B are Links {1, 2} and Links {3, 4}. Acceleration is zero, and the net elevation change is also zero. When elevation is not considered, the path with the least energy cost is Path {3, 4}. However, when grades are accounted for, the energy required to traverse Links 1 and 4 is greatly reduced (but not negative because of a lack of ICEV regeneration) and the energy required to traverse Links 2 and 3 is increased. Path {1, 2} includes a longer downhill slope, followed by a short positive grade, 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 increase in energy consumption. When the topology of the demonstration network is considered, the minimum-energy path becomes Path {1, 2}. Thus, drivers who chose a path to minimize energy consumption but who did not account for grades actually experienced an increase in overall energy consumption, despite behavior choices intended to achieve the opposite effect.

City Networks Demonstration

Energy consumption calculated with and without the inclusion of grades was considered on two city networks with a topology with a moderate elevation. The downtown Austin, Texas, network has 171 zones, 546 intersections, 1,247 links, 62,836 trips, and an average absolute grade of 0.95°. The Nicosia, Cyprus, network has 702 zones, 13,456 intersections, 22,741 links, 58,678 trips, and an average absolute grade of 0.80°. Both networks were generated from city planning

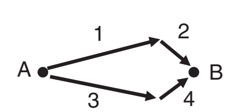


FIGURE 1 Demonstration network.

TABLE 2 Results for Demonstration Network

Link	Length (km)	Speed (km/h)	Travel Time (s)	Elevation (km)	Grade (degrees)	Energy Consumption (W-h) Without Grades	Energy Consumption (W-h) With Grades
1	3	77	140	–0.1	–1.91	4,009.4	270.9
2	1	77	47	0.1	5.71	1,336.5	5,102.9
3	3	60	180	0.1	1.91	3,063.7	6,846.8
4	1	60	60	–0.1	–5.71	1,021.2	115.9

data. Although the topology is not flat, the results for many cities with greater changes in elevation may be more exaggerated.

To find link grades, the Google Elevation advanced programming interface was used to determine the elevation at each node. Link grades were assumed to be constant on the basis of 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 link length of 0.14 km and a total link distance of 3,244.6 km in Nicosia, this precision is sufficient to demonstrate the effect of grades on energy consumption.

Verification of Energy Model

Although the focus of this work is on the change in vehicle energy consumption because of the added consideration of grade and not a prediction of aggregate energy consumption, an effort was made to ensure that the results for absolute vehicle energy consumption were not unreasonable. With the use of 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 for the characteristic vehicle on the Nicosia network. The difference from the reported fuel efficiency of 9.01 km/L is only 10.9% for Austin and 35.4% for Nicosia (*3*). This difference may be due to specific network characteristics or the assumptions made to calculate acceleration in the DTA model.

Results for City Networks

Figure 2 displays the average change in energy consumption caused by the inclusion of grade for all vehicles on the downtown Austin and Nicosia networks. The horizontal axis shows the average weighted path grade, which is the average of all the link grades on the vehicle's path weighted by link length. A negative average path grade indicates that the path is more downhill in nature, and a positive average path grade indicates that the path is uphill overall. The vertical axis of Figure 2 shows the change in vehicle energy consumption as a result of the inclusion of grade in the energy consumption calculations.

Several observations about nonintuitive network behavior can be made from the results. Although, on average, a negative path grade resulted in a decrease in vehicle energy consumption and a positive path grade resulted in an increase in vehicle energy consumption, this was not necessarily true in all cases. This finding might be the result of complex interactions between traffic and energy consumption on a grade, a result that would be difficult to capture without the use of mesoscopic traffic models such as VISTA. Moreover, the histogram displayed in Figure 2 did not appear to be symmetric in either network. These two observations indicate that both at the individual vehicle level and on an aggregate scale, consideration of road elevation changes the results of the energy consumption models. In addition, one is not able to intuit whether an estimate that does not include grade overestimates or underestimates vehicle energy consumption. In downtown Austin, the lack of inclusion of grades resulted in a decrease in the predicted total energy consumption of 10.5%; in Nicosia, the decrease was 3.6%.

TABLE 3 Energy Consumption in Demonstration Network

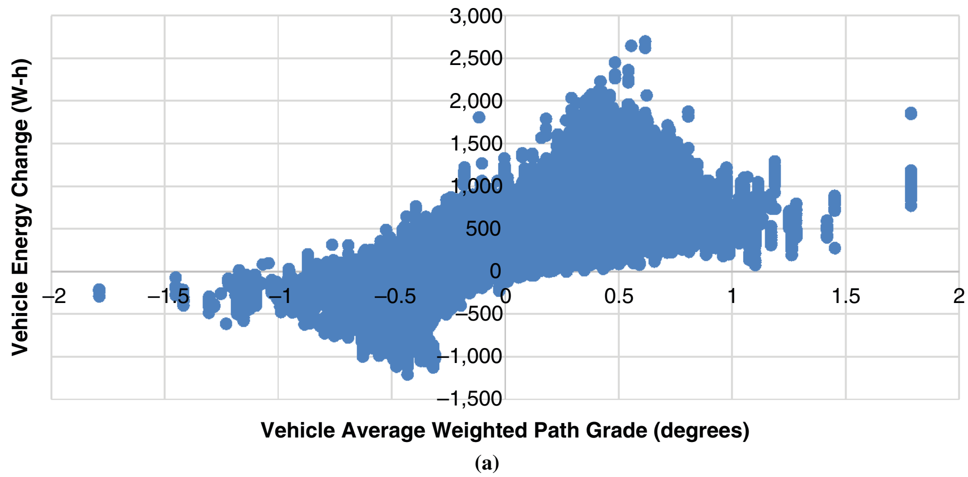
Path	Links	Energy Consumption (W-h) Without Grades	Energy Consumption (W-h) With Grades
1	{1, 2}	5,345.9	5,373.8
2	{3, 4}	4,084.9	6,962.7
1 – 2	{1, 2} – {3, 4}	1,260.9	–1,588.9

Impact on Ecorouting

This section demonstrates the impact of the inclusion of grades when paths with the least energy cost are computed. An ecorouting experiment was performed in which the minimum-energy ecopaths for between 5% and 30% of all vehicles were found for the 100% demand cases in downtown Austin and Nicosia. In the first stage of the experiment, minimum-energy ecopaths in the DTA network state were identified by consideration and lack of consideration of grades. This ecopath represents the path identified by the in-vehicle routing device to consume a minimum amount of energy, which was calculated by use of the link energy costs at vehicle departure. The link energy costs were updated every 15 min.

In the second stage, a percentage of the vehicles was moved to the ecopath and the new vehicle energy consumption was computed by use of the grades. The second stage represents the actual energy cost experienced by the vehicle, which would include the effect of grade. This ecorouting experiment demonstrates the impact achieved when grade is either accounted for or not accounted for in the identification of the ecopath.

Figure 3 shows the results from the ecorouting experiment, in which the horizontal axis represents the percentage of vehicles that have chosen to follow an ecoroute and the vertical axis shows the average change in energy consumption because of rerouting for each vehicle. In both networks, the results demonstrate that the average energy consumption for vehicles whose drivers took the ecoroute was consistently less when grades were included in the stage of identification



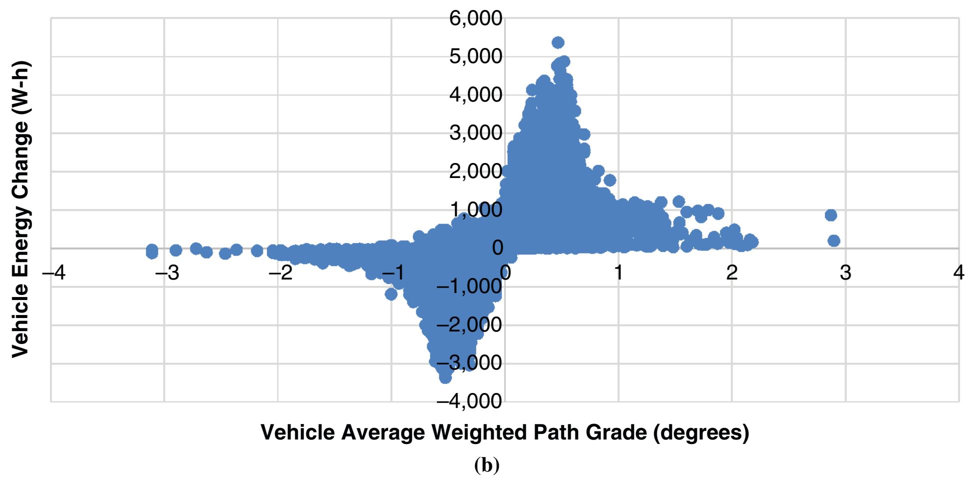


FIGURE 2 Energy change for individual vehicles because of inclusion of impact of link grade for (*a*) downtown Austin and (*b*) Nicosia networks.

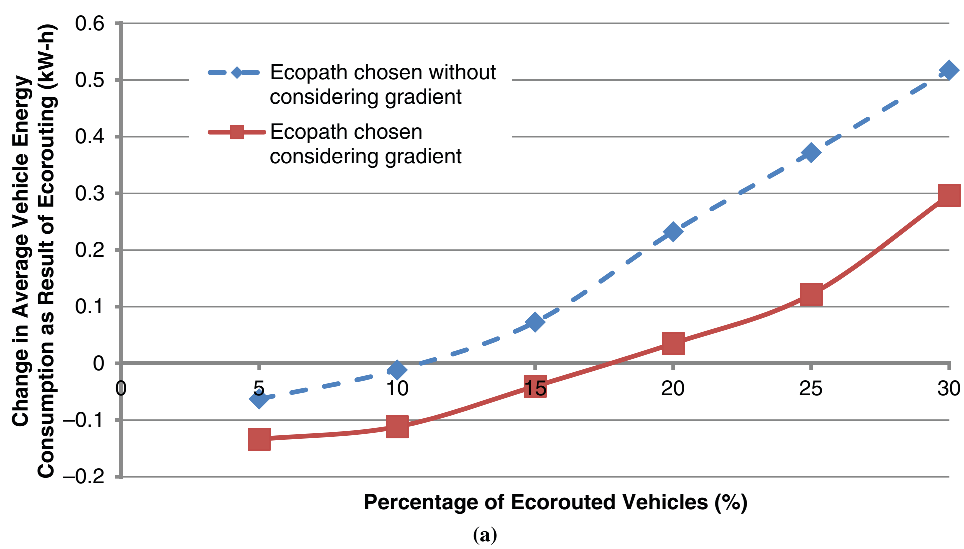
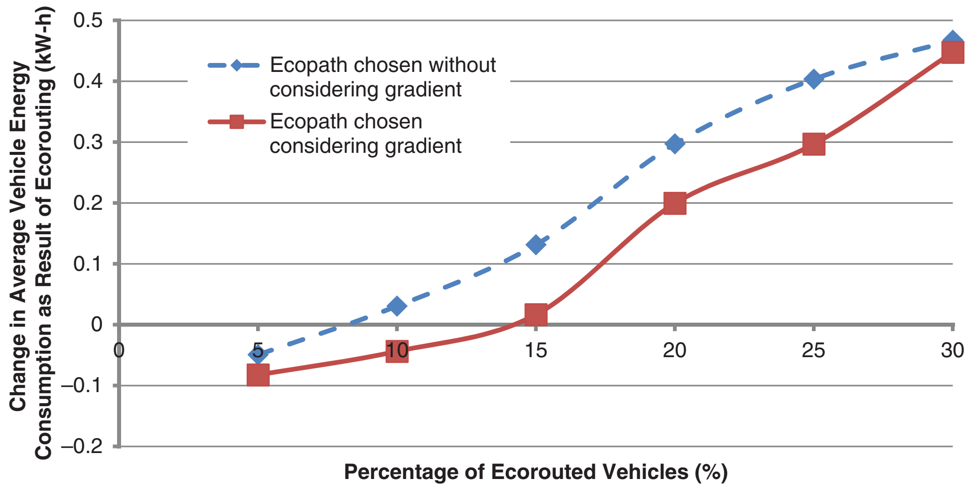


FIGURE 3 Change in energy consumption per vehicle for drivers using ecorouting by percentage: (*a*) downtown Austin network.

(continued on next page)



(b)

FIGURE 3 *(continued)* **Change in energy consumption per vehicle for drivers using ecorouting by percentage: (*b*) Nicosia network.**

of the ecopath. These results are not unexpected because the wrong path could be identified if grade is not accounted for when the ecopath is chosen. However, these results further demonstrate the importance of the inclusion of grade in ecorouting. If grade is not considered, the energy consumed on a route may actually be unintentionally increased.

Figure 3 also shows that for greater percentages of drivers using ecorouting, the amount of energy consumed actually increases. This situation occurs more often when drivers consider grade in their ecoroute choice (~17% for Austin and ~14% for Nicosia) because the ecopaths became more congested because of additional vehicles, and equilibrium effects were not included, so vehicles did not change paths because of congestion or additional energy consumption. Although this scenario is not perfectly representative of real ecorouting behavior, two possible conclusions can still be drawn from these results:

1. The lack of inclusion of grade during the identification of the ecopaths can result in the misidentification of an ecopath and, therefore, overestimation of energy savings or can even result in an increase in energy consumption.
2. Empirical results suggest that a greater percentage of trips can be rerouted before an energy increase occurs when grade is considered. After this point, ecopaths calculated on the basis of historical data would also lead to an increase in energy consumption, thereby suggesting a need for more complex routing algorithms. This point occurs when a lower percentage of drivers who are using ecorouting does not account for grade.

CONCLUSIONS

Vehicle energy consumption is an important reflection of vehicle performance and is also a relevant concern in the evaluation of the impact of traffic policies and evaluations of transportation projects, including infrastructure design and intelligent transportation system technologies. This work demonstrated the importance of an accounting for changes in road elevation in models of transport vehicle energy consumption and focused on the application of ecorouting and networkwide vehicle energy consumption.

A novel approach integrating road load equations and the DTA tool VISTA used the downtown Austin, Texas, and Nicosia, Cyprus, networks to show that the energy consumption of individual vehicles can vary significantly, even in networks with relatively flat topologies. Results from the two networks also indicated that the networkwide change in energy consumption because of road elevation is not symmetric in nature, and it is not possible to determine intuitively whether the energy consumption of individual vehicles will increase or decrease on the basis of the average path grade. It may be predicted that networks with greater variations in road elevation will show even more exaggerated results.

In addition, an exploration of ecorouting, in which drivers choose the shortest path that consumes the least amount of energy, demonstrated that identification of the ecopath can actually lead to an increase in vehicle energy consumption if grade is not accounted for. Finally, if road grade is not accounted for, incorrect ecoroutes may be chosen, and again, energy consumption may actually increase. Although this work focused on the application of ecorouting and networkwide vehicle energy consumption, similar miscalculations from a lack of inclusion of road elevation may result when other vehicle energy consumption models are applied.

The current work evaluated the impact of changes in road elevation on energy consumption by focusing on the light-duty vehicle fleet, but future work will expand the current tool to include vehicles that use alternative technologies. Because of the flexible underlying framework of the DTA model, a multiclass expansion of the current model could help network planners more realistically evaluate energy consumption in a city because vehicle types other than passenger cars may experience more significant changes in energy consumption when energy consumption is predicted by the inclusion of grade. For instance, heavy vehicles, which typically accelerate more slowly, may require a greater proportion of cruise energy consumption to travel uphill. Furthermore, many electric vehicle drivers must be conscious of range limitations, and the more accurate predictions of energy consumption obtained when grades are included might assist with the range anxiety of drivers of such vehicles.

Another potential topic of interest to focus on will be the differences in energy consumption for vehicles that use alternative technologies, particularly electric vehicles. It is especially important to account for changes in elevation when the energy consumption of electric vehicles is modeled because of the added effect of regenerative braking.

ACKNOWLEDGMENTS

This research was made possible in part by the generous support of National Information Communications Technology Australia Ltd. (NICTA). NICTA is funded by the Australian Government and is represented by the Department of Broadband, Communications, and the Digital Economy and the Australian Research Council through the Information Communications Technology Centre of Excellence program.

REFERENCES

1. Markel, T., A. Brooker, T. Hendricks, V. Johnson, K. Kelly, B. Kramer, M. O'Keefe, S. Sprik, and K. Wipke. ADVISOR: A Systems Analysis Tool for Advanced Vehicle Modeling. *Journal of Power Sources,* Vol. 110, No. 2, 2002, pp. 255–266.
2. Vijayagopal, R., N. Shidore, S. Halbach, L. Michaels, and A. Rousseau. *Automated Model Based Design Process to Evaluate Advanced Component Technologies.* SAE International, Warrendale, Pa., 2010.
3. Simpson, A. G. *Parametric Modelling of Energy Consumption in Road Vehicles.* University of Queensland, Brisbane, Australia, 2005.
4. Joumard, R., M. Andre, R. Vidon, P. Tassel, and C. Pruvost. Influence of Driving Cycles on Unit Emissions from Passenger Cars. *Atmospheric Environment,* Vol. 34, No. 27, 2000, pp. 4621–4628.
5. Dowling, R. *Traffic Analysis Toolbox,* Vol. VI, *Definition, Interpretation, and Calculation of Traffic Analysis Tools Measures of Effectiveness.* Report FHWA-HOP-08-054. FHWA, U.S. Department of Transportation, 2007.
6. Hickman, J., D. Hassel, R. R. Joumard, Z. Samaras, and S. Sorenson. *Methodology for Calculating Transport Emissions and Energy Consumption.* UK Transport Research Laboratory, Berks, United Kingdom, 1999.
7. Gardner, L. M., M. Duell, and S. T. Waller. A Framework for Evaluating the Role of Electric Vehicles in Transportation Network Infrastructure Under Travel Demand Variability. *Transportation Research Part A: Policy and Practice,* Vol. 49, Mar. 2013, pp. 76–90.
8. Duell, M., L. Gardner, and S. T. Waller. Multiobjective Traffic Network Design Accounting for Plug-in Electric Vehicle Energy Consumption. Presented at 92nd Annual Meeting of the Transportation Research Board, Washington, D.C., 2013.
9. Rakha, H., and Y. Ding. Impact of Stops on Vehicle Fuel Consumption and Emissions. *Journal of Transportation Engineering,* Vol. 129, No. 1, 2002, pp. 23–32.
10. Ahn, K., H. A. Rakha, A. Trani, and M. Van Aerde. Estimating Vehicle Fuel Consumption and Emissions Based on Instantaneous Speed and Acceleration Levels. *Journal of Transportation Engineering,* Vol. 128, No. 2, 2002, pp. 182–190.
11. Fellendorf, M. VISSIM: A Microscopic Simulation Tool to Evaluate Actuated Signal Control Including Bus Priority. *Proc., 64th ITE Annual Meeting,* 1994, pp. 1–9.
12. Cameron, G. D., and G. I. Duncan. PARAMICS—Parallel Microscopic Simulation of Road Traffic. *Journal of Supercomputing,* Vol. 10, No. 1, 1996, pp. 25–53.
13. Barceló, J., J. L. Ferrer, and L. Montero. *AIMSUN: Advanced Interactive Microscopic Simulator for Urban Networks,* Vol. I, *System Description,* and Vol. 2, *User's Manual.* Departamento de Estadística e Investigacion Operativa, Facultad de Informatica, Universidad Politecnica de Cataluna, Barcelona, Spain, 1989.
14. Fernández, P., and J. Long. Grades and Other Loads Effects on On-Road Emissions: An On-Board Analyzer Study. Presented at Fifth CRC On-Road Vehicle Emission Workshop, 1995.
15. Hassel, D., and F. J. Weber. *Gradient Influence on Emission and Consumption Behaviour of Light and Heavy Duty Vehicles.* MEET project deliverable, 1997.
16. Park, S., and H. A. Rakha. Energy and Environmental Impacts of Roadway Grades. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1987,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 148–160.
17. Boriboonsomsin, K., and M. Barth. Impacts of Road Grade on Fuel Consumption and Carbon Dioxide Emissions Evidenced by Use of Advanced Navigation Systems. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2139,* Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 21–30.
18. Chang, D. J., and E. K. Morlok. Vehicle Speed Profiles to Minimize Work and Fuel Consumption. *Journal of Transportation Engineering,* Vol. 131, No. 3, 2005, pp. 173–182.
19. Auer, D. *Energy Consumption of Electrical Driven Regular Buses Dependent on Route Characteristics and Operational Requirements.* http://www.trolley-project.eu/index.php?id=114, 2012.
20. Bullock, K. J. Driving Cycles. Presented at SAE-A/ARRB 2nd Conference on Traffic Energy and Emissions, Melbourne, Australia, 1982.
21. Ziliaskopoulos, A. K., and S. T. Waller. An Internet-Based Geographic Information System That Integrates Data, Models and Users for Transportation Applications. *Transportation Research Part C: Emerging Technologies,* Vol. 8, No. 1–6, 2001, pp. 427–444.
22. Daganzo, C. F. The Cell Transmission Model: A Dynamic Representation of Highway Traffic Consistent with the Hydrodynamic Theory. *Transportation Research Part B: Methodological,* Vol. 28, No. 4, 1994, pp. 269–287.
23. Daganzo, C. F. The Cell Transmission Model. Part II. Network Traffic. *Transportation Research Part B: Methodological,* Vol. 29, No. 2, 1995, pp. 79–93.

The Transportation and Air Quality Committee peer-reviewed this paper.