

# UC Riverside

## 2018 Publications

### Title

Dynamic En-Route Eco-Navigation: Strategy Design, Implementation and Evaluation

### Permalink

<https://escholarship.org/uc/item/32q8j300>

### Authors

Li, W.  
Wu, G.  
Yao, D.  
et al.

### Publication Date

2018-11-04

Peer reviewed

# Dynamic En-Route Eco-Navigation: Strategy Design, Implementation and Evaluation

Weixia Li, Guoyuan Wu, *Senior Member, IEEE*, Danya Yao, Yi Zhang, *Member, IEEE*, Matthew J. Barth, *Fellow, IEEE*

**Abstract**— Transportation activities account for a significant fraction of the world’s total energy consumption and emissions. In recent years, reducing a vehicle’s energy consumption and emissions has become a research topic with ever-increasing interest, especially in the area of intelligent transportation systems (ITS). Among a variety of ITS applications, environmentally-friendly navigation (or eco-routing), which aims at finding a minimal energy or minimal emissions route, has the potential to significantly reduce energy consumption and total emissions. Previous research on environmentally-friendly navigation mainly focuses on pre-trip eco-routing. However, this approach may not be optimal due to the highly dynamic evolution of traffic conditions. In contrast, carrying out dynamic en-route eco-navigation can potentially further improve environmental sustainability. This paper presents a methodology for dynamic en-route eco-navigation research, in which details for strategy design, implementation and evaluation are elaborated. Utilizing this methodology, a case study has been carried out using a well-evaluated mesoscopic energy consumption model applied to a Beijing’s expressways network. Results demonstrate that the proposed dynamic en-route eco-navigation in this study is beneficial in improving environmental sustainability while not compromising mobility.

## I. INTRODUCTION

On-road vehicles have been regarded as one of major contributors to world-wide energy consumption and pollutant emissions. Statistics from the China Vehicle Environmental Management Annual Report 2017 have indicated approximately 44.73 million tons of vehicle-generated pollutants in China in 2016 [1]. A study on source analysis of particulate matter 2.5 (PM<sub>2.5</sub>) showed that 31.1% of the PM<sub>2.5</sub> emissions in Beijing was produced by motor vehicles [2]. Further, in the United States, 27% of the total greenhouse gases (GHG) was attributed to the transportation sector in 2015 [3]. As a result, improving energy efficiency and reducing vehicle energy consumption and emissions have attracted an ever-increasing public interest, especially in the developing countries with frequent pollution problems such as China. A variety of counter-measures have been introduced to

reduce vehicle energy consumption and emissions, ranging from stricter tailpipe emission standards, promotion of alternative fuel vehicles, and the development of numerous advanced driver assistance systems (ADAS) with the target of promoting “greener” traveling. Among these applications, eco-navigation, which is dedicated to searching for the most environmentally-friendly route, has proven to be effective in reducing energy consumption and emissions [4-5].

Scholars from different countries have been dedicated to the development of eco-navigation applications for decades. An exploratory research in Sweden proposed a driver support tool to optimize route choice for the lowest fuel consumption [6]. In the United States, eco-routing studies have mainly been explored from two different perspectives, i.e., user’s perspective to calculate the eco-route for individual vehicle and operator’s perspective to calculate eco-route assignment for the networked traffic. As an example of the first perspective, an environmentally-friendly navigation system was thoroughly developed by Boriboonsomsin et al. [7]. With the system, the optimal routes in terms of fuel consumption and travel time from the Los Angeles Airport to downtown Los Angeles were compared, and results presented that vehicle fuel consumption could be reduced by 25% when taking the least fuel consumption route, with the travel time only increasing by 8%. From the second perspective, Rakha et al. has designed, implemented and evaluated the eco-routing strategy via INTEGRATION [9] and VT-Micro [10]. Two eco-routing algorithms, i.e., an eco-sub-population feedback assignment (ECO-SFA) and an eco-agent feedback assignment (ECO-AFA), were proposed and applied to a simple network with two alternative routes [9] and two real-world networks (downtown Cleveland and Columbus) [11]. Research results demonstrated approximately 1.94% and 5.59% fuel consumption reductions on average for different eco-vehicle penetration rates in the Cleveland and Columbus networks. Zhao et al. developed a simplified, trip-based macro-model to estimate fuel consumption, CO and NO<sub>x</sub> emissions [12] based on five readily available traffic attributes (including trip speed limit, facility type, congestion level, trip length and road grade) and fuel consumption and emissions data from a macroscopic TRANSIMS-MOVES model (TRansportation ANalysis SIMulation System [13] and MOrtor Vehicle Emission Simulator [14]). The developed models were applied to the eco-navigation studies for the Burlington network [12] and the Buffalo network [15]. 2.2% energy savings were obtained for the Burlington network with only 1.9% efficiency penalty. For the Buffalo network, CO emission reduction ranged from 26% to 32% with the increase of travel time between 11% and 35% under different market penetration rates.

\* This research was supported by China Postdoctoral Science Foundation (grant number 2017M620782).

W. Li is with Department of Automation, Tsinghua University, Beijing 100084 China (e-mail: [wx-li11@mails.tsinghua.edu.cn](mailto:wx-li11@mails.tsinghua.edu.cn))

G. Wu is with the Center for Environmental Research & Technology, UC Riverside, CA 92507 USA (e-mail: [gywu@cert.ucr.edu](mailto:gywu@cert.ucr.edu)).

D. Yao is with Department of Automation, Tsinghua University, Beijing 100084 China (e-mail: [yaody@tsinghua.edu.cn](mailto:yaody@tsinghua.edu.cn))

Y. Zhang is with Department of Automation, Tsinghua University, Beijing 100084 China (e-mail: [zhyi@mail.tsinghua.edu.cn](mailto:zhyi@mail.tsinghua.edu.cn))

M. Barth is with the Center for Environmental Research & Technology, UC Riverside, CA 92507 USA (e-mail: [barth@ee.ucr.edu](mailto:barth@ee.ucr.edu)).

In China, eco-navigation has also been explored from mainly two different angles. The first one is estimating link-based fuel consumption and emission factors in terms of link driving pattern and then searching for the eco-route [16]. Kang et al., compared the eco-route and the time priority route from Beihang University to ShouDi shopping center in Beijing using the International Vehicle Emissions (IVE) model [17] and obtained 19% CO<sub>2</sub> reduction and 27% time increase for the eco-route. From the second angle, Yao et al., developed fuel consumption and emission models based on field test data from portable emission measurement system (PEMS) [18]. Further eco-routing study for a randomly selected origin-destination pair in Beijing demonstrated that driving through the eco-route might consume 5.3% less fuel with 3.8% increase in travel time.

The aforementioned studies have demonstrated the benefits of eco-navigation on energy conservation and emission reduction. However, a well validated model for trip-based fuel consumption and emission calculation is still deficient for eco-routing research in China. In addition, previous research focus on either static comparison (for pre-trip time optimal route and eco-route) or dynamic comparison (en-route time optimal route and eco-route), systematic comparison among route with no eco-navigation, eco-navigation without en-route changes and en-route eco-navigation is needed to quantitatively stand out the effects of dynamic en-route eco-navigation.

The objective of this paper is to explore dynamic en-route eco-navigation in China. A methodology including strategy design, implementation and evaluation is proposed, which could be transferable to other areas or countries. With the proposed methodology, an innovative mesoscopic modeling method in authors' previous work, i.e., conditional operating mode based modeling, was applied to field test data in Beijing to establish the energy consumption model for eco-navigation research. In the end, the strategy was implemented and evaluated in a microscopic simulation network in Beijing.

The remainder of the paper is structured into three sections. Section II describes the details of proposed methodology, including strategy design, implementation and evaluation. A case study in which the dynamic en-route eco-navigation is simulated, analyzed and presented in Section III. The major findings and conclusions are summarized in Section IV.

## II. METHODOLOGY

The methodology of dynamic en-route eco-navigation is composed of three parts. The strategy design part identifies the major functions and their specific approaches. The implementation part implements the designed strategy with a suite of simulation tools. Programs for each function of the strategy are coded and tested. The evaluation part determines the metrics used in assessing strategy effectiveness. Further, methods to obtain the corresponding metrics are described.

### A. Strategy Design

Major components in dynamic en-route eco-navigation strategy include link cost calculation, eco-route planning, and

route control. Link cost calculation part provides the computing basis for vehicle energy consumption or emissions. Eco-route planning part calculates the optimal path. Route control part produces comparative results for further analysis.

### 1) Link Cost Calculation

Link cost is defined as the energy or emissions that a vehicle will consume or produce when passing through the specific link. The average link speed is usually available to estimate the link-level energy consumption or emissions. Therefore, a mesoscopic model is necessary to relate energy consumption or emission factors to average link speed. A recent work by the authors performed a comparison on different data segregation methods for mesoscopic energy or emission modeling [19], and proposed a novel modeling method based on conditional operating mode (COPMode). Results demonstrated the superiority of the COPMode based model in estimating trip-based energy consumption. Hence, the COPMode based model is selected to calculate link costs.

The COPMode based energy consumption model can be summarized with Eq. (1) to Eq. (5).

$$COPMode_j = (i, k) \text{ for } OpMode_j = i \text{ and } v_j \in [k-1, k) \quad (1)$$

$$\overline{FR}_{COPMode_{i,k}} = \frac{\sum FR_j}{l_i} \quad \forall COPMode_j = (i, k) \quad (2)$$

$$FR_{COPMode_j} = \overline{FR}_{COPMode_{i,k}} \text{ for } COPMode_j = (i, k) \quad (3)$$

$$\overline{v}_i = \frac{\sum_{j=60*(i-1)+1}^{60*i} v_j}{60} \quad i = 1, 2, \dots, \left\lfloor \frac{\max(j)}{60} \right\rfloor \quad (4)$$

$$\overline{FF}_i = \frac{\sum_{j=60*(i-1)+1}^{60*i} FR_{COPMode_j}}{\sum_{j=60*(i-1)+1}^{60*i} v_j / 3.6} \quad i = 1, 2, \dots, \left\lfloor \frac{\max(j)}{60} \right\rfloor \quad (5)$$

where  $COPMode_j$  is vehicle conditional operating mode in the  $j$ th second;  $OpMode_j$  is vehicle operating mode in the  $j$ th second;  $\overline{FR}_{COPMode_{i,k}}$  is the average fuel consumption rate corresponding to  $COPMode_{i,k}$ ;  $FR_j$  is the fuel consumption rate in the  $j$ th second;  $l_i$  is the number of fuel consumption rate data with  $COPMode_j = (i, k)$ ;  $FR_{COPMode_j}$  is the reconstructed fuel consumption rate corresponding to  $COPMode_{i,k}$ ;  $\overline{v}_i$  is the average speed in the  $i$ th snippet;  $\overline{FF}_i$  is the average fuel consumption factor in the  $i$ th snippet.

With the COPMode modeling method, field test datasets were collected and utilized to establish mesoscopic energy consumption model. The validated model is presented in Eq. (6). For more details about the modeling and validation process, please refer to [19].

$$\log FF_{m,n} = 4.63 * 10^{-8} * v^4 - 1.18 * 10^{-5} * v^3 + 1.2 * 10^{-3} * v^2 - 5.39 * v - 0.3621 \quad (6)$$

Link costs are calculated with Eq. (7), where  $FF_{m,n}$  is the fuel consumption factor corresponding to the link from node  $m$  to node  $n$ , and  $LinkLength_{m,n}$  is the geometric length of the link that connects node  $m$  to node  $n$ , and  $LinkCost_{m,n}$  will be set as infinite if two nodes are not physically connected.

$$LinkCost_{m,n} = FF_{m,n} * LinkLength_{m,n} \quad (7)$$

## 2) Dynamic Eco-Route Planning

Eco-route for the specified origin and destination (OD) can be calculated when the link costs for the whole road network are updated. It is noted that this research is focused on the dynamic en-route eco-navigation, where the optimal route should be updated as the target vehicle is driving on road. Therefore, the dynamic eco-route planning may be regarded as a series of path planning problem with the origin being updated as necessary. Numerous algorithms have been proposed and evaluated to solve the shortest path problem. And Dijkstra algorithm [8] is an effective one in small size networks. In this research, Dijkstra algorithm is used to calculate the optimal route, and other algorithms (e.g., A\* algorithm) can also be alternatives to implement path planning.

The principle of Dijkstra algorithm is to rank the nodes by an increasing sequence of the travel cost. The pseudo codes of lowest cost path search can be summarized as follows:

```
function Dijkstra(Graph, source):
  create vertex set Q
  for each vertex v in Graph: // Initialization
    cost[v] ← INFINITY
    prev[v] ← UNDEFINED
    add v to Q
  cost[source] ← 0
  while Q is not empty:
    u ← vertex in Q with min cost[u]
    remove u from Q
    for each neighbor v of u:
      alt ← cost[u] + LinkCost(u, v)
      if alt < cost[v]:
        cost[v] ← alt
        prev[v] ← u
  return cost[], prev[]
```

## 3) Dynamic Route Control

Typically, drivers are not obligated to follow the recommended path and there might be certain compliance rate for drivers when applying dynamic en-route eco-navigation in the real world. However, it is highly suggested to control vehicles' path selections to evaluate strategy effectiveness. In addition, dynamic en-route eco-navigation can be further applied to autonomous vehicles, where dynamic route control will be mandatory. In this research, dynamic route control is carried out in simulation. The basic process is identifying real-time vehicle location, comparing the current link with the link list in the optimal route, determining the next link, assigning next link for the specified vehicle.

### B. Strategy Implementation

Traffic state and vehicle path selection influence each other to a great extent for which conducting navigation according to real time traffic state is highly necessary. Simulation model is usually an easier and better way to provide real time traffic information. Therefore, the proposed en-route eco-navigation strategy in this study is implemented via simulation model Paramics (Parallel Microscopic Simulator, see <http://www.paramics-online.com>). Three tools

of Paramics, i.e., Modeler, Estimator and Programmer, are used in this research for road network establishment, OD calculation and strategy coding, respectively.

In this research, a road network of the Beijing expressways network is modeled via Modeler. Parameters of the modeled network are adjusted according to actual demands, and are completely controlled to support the before-and-after comparison on strategy effects. The OD matrix is generated with Estimator, a stand-alone tool designed for OD estimation, based on the assumption of LOS (level-of-service) B [20]. For validation purpose, the traffic network only includes expressways in this research. Core functions of dynamic en-route eco-navigation, i.e., link cost calculation, dynamic eco-route planning and dynamic route control, are coded with Programmer using Application Programming Interfaces (APIs). In the APIs, some link-based "qpg" functions (functions used to retrieve data from within either the simulation or graphics engines inside Paramics) are used to obtain link speed, which are further used with the energy consumption model to calculate link costs. Some vehicle-based "qpg" functions are used to acquire real-time vehicle location and destination for path planning. In addition, some vehicle-based "qps" (functions used to set a data value or change or add to the view displayed) and "qpo" functions (functions used to define a function in the plugin that can override the standard default behavior inside Paramics) are used to control vehicle's route.

### C. Strategy Evaluation

The evaluation work in this research mainly include two aspects, i.e., strategy influence on vehicle path selection, strategy influence on environmental sustainability and mobility performance.

For the evaluation of vehicle path selection, Paramics is capable of recording and outputting the trajectories of specified vehicles, based on which the traveling paths for the same vehicle under conditions of no eco-navigation, eco-navigation without en-route changes and dynamic en-route eco-navigation are compared. For the evaluation of environmental sustainability and mobility performance, Paramics can calculate the travel time of certain vehicles, and CMEM (Comprehensive Modal Emission Model), a microscopic model designed to predict second-by-second energy consumption and emissions [21], is applied to computing trip-based energy consumption. In the end, statistical analysis is carried out to evaluate strategy effectiveness.

## III. CASE STUDY AND RESULTS

In this research, a simulation network of Beijing expressways has been established to evaluate the dynamic en-route eco-navigation strategy. A case study has been carried out for a randomly selected vehicle in the network. Details about the simulation setup, simulation scenarios, and comparative results are depicted below.

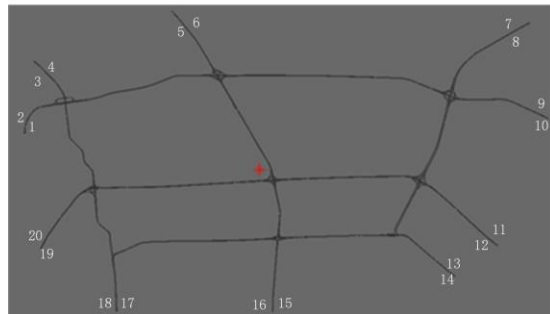
### A. Research Network

The network used in this paper is illustrated in Fig. 1a), composed of three vertical and three horizontal major road

segments of expressways in Beijing. All selected road segments are primary expressways in Beijing, with heavy traffic during peak periods. In this network, several alternative routes are available for each OD pair. Detailed parameters about the network are presented in TABLE I.



a) Research network - Beijing expressway network



b) Simulation network and zone numbering

Figure 1. Research network and simulation network

TABLE I. PARAMETERS OF THE RESEARCH NETWORK

Road Name	Number of Lanes	Length (km)	Width (m)	Speed Limit (km/h)
North 5th Ring Road	Two-way 6 lanes	20	2*11.25	100
North 4th Ring Road	Two-way 8 lanes	15	2*15	80
North 3rd Ring Road	Two-way 6 lanes	10	2*11.25	80
Wanquanhe Expressway	Two-way 6 lanes	7	2*11.25	80
G6 Jingzang Expressway	Two-way 6 lanes	9	2*11.25	100
Jingcheng Expressway	Two-way 6 lanes	8	2*11.25	80

### B. Simulation Setup

In accordance with the parameters of the real-world road network, the simulation network is set as the same topology and dimensions in Paramics Modeler, as presented in Fig. 1b). For the convenience of analysis, the traffic zones (as the sources and sinks for vehicle generation and absorption) in the network are numbered as 1 to 20. Zones denoted with odd numbers are origins and the ones denoted with even numbers are destinations.

The OD matrix of the network is generated from Paramics Estimator. The dynamic traffic information is updated by the loop detectors in the network every minute, and the API for link cost calculation is called once the traffic information is updated. Based on the dynamic link cost information, en-route

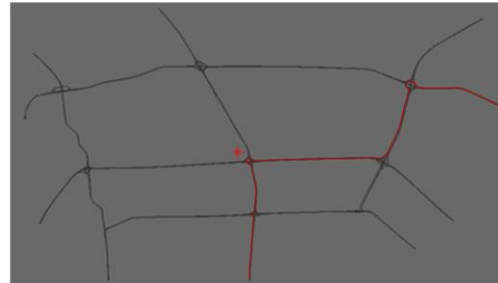
eco-path is calculated every five minutes as long as the target vehicle is driving in the network.

### C. Results and Analysis

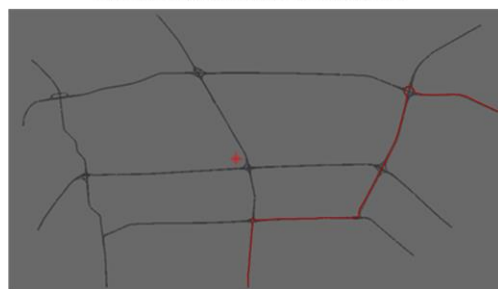
To evaluate the strategy effectiveness, a vehicle traveling from zone 9 to zone 16 is randomly selected to apply the dynamic en-route eco-navigation. Vehicle path selection and energy consumption when following the navigation guidance are compared with those without guidance.

#### 1) Influence on Path Selection

Fig. 2 presents the path selections of the specified vehicle before-and-after the dynamic en-route eco-navigation. Fig. 2a) represents the default traveling path in Paramics, which is the pre-trip optimal path calculated to minimize travel time, while Fig. 2b) shows the actual path of the vehicle when following the en-route eco-navigation guidance (path update every five minutes). In this example, it turns out that the en-route optimal path is the same as the default path (by Paramics) at the beginning of simulation (i.e., when the vehicle is released), which means the eco-navigation without en-route changes (i.e., the pre-trip eco-path) recommends the same path as Fig. 2a). However, the traffic conditions of G6 Jingzang Expressway (refer to Fig. 1a) for road segment location) changed dramatically (becoming congested) as the vehicle was driving along Jingcheng Expressway. Then, the en-route optimal eco-path got updated (i.e., changed from Fig. 2a) to Fig. 2b)). This result demonstrates the difference of dynamic en-route eco-path and pre-trip eco-path, which also proves the necessity of the en-route eco-navigation.



a) traveling path without navigation



b) traveling path with navigation

Figure 2. Path selection without vs. with navigation.

#### 2) Influence on Environmental Sustainability and Mobility

For the analysis of environmental sustainability and mobility performance, two measures of effectiveness (MOEs), i.e., trip-based fuel consumption (on the environmental influence) and travel time (on the mobility influence), are used in this research. TABLE II presents vehicle energy

consumption and travel time for the vehicle without and with eco-navigation. Since the pre-trip eco-navigation has the same results as the pre-trip time priority navigation, the results for the two scenarios are denoted with no eco-navigation in the table. The relative difference is calculated via Eq. (8).

$$Relative\ difference = \frac{MOE_{eco} - MOE_{noneco}}{MOE_{noneco}} \times 100\% \quad (8)$$

where  $MOE_{eco}$  is the metric with dynamic en-route eco-navigation, and  $MOE_{noneco}$  is the metric without eco-navigation or with pre-trip eco-navigation.

TABLE II. MEASURES OF EFFECTIVENESS (MOEs) FOR AN EXAMPLE TRIP WITH AND WITHOUT DYNAMIC EN-ROUTE ECO-NAVIGATION

Path type	Fuel consumption	Travel time
No eco-navigation	734.30g	979s
Dynamic eco-navigation	714.51g	959s
Relative difference	-2.70%	-2.04%

Results in TABLE II demonstrate that vehicle energy consumption is reduced when following the dynamic en-route eco-navigation. It verifies the strategy effectiveness on energy conservation and emission reduction. Moreover, vehicle travel time is also reduced since the eco-navigation is carried out in a dynamic and en-route manner. Therefore, the proposed strategy is beneficial in improving both vehicle energy efficiency and mobility in this case.

### 3) Statistical Analysis

To get further insight into the effectiveness of dynamic en-route eco-navigation, statistical analysis was carried out on 40 vehicles with different departure times. For each individual vehicle, before-and-after simulations were conducted where the proposed routing algorithm was turned off and on for comparison. For each pair of simulations, energy consumption and travel time of the target vehicle were calculated based on actual vehicle trajectories, and the results are demonstrated in Fig. 3 and Fig. 4. As observed in Fig. 3, vehicles with en-route eco-navigation consistently consume less fuel than the baseline vehicles. However, the benefits/disbenefits in travel time due to the introduction of eco-navigation varies with departure times. According to Fig. 4, for most samples with departure time earlier than 2200s (in simulation time) after the simulation started, equipped-vehicles' travel times are slightly higher than baseline vehicles. An explanation for this is that the traffic was light at the beginning, and vehicles travelling at higher speeds require more energy. Therefore, the dynamic en-route eco-navigation recommended the longer-duration but more fuel-efficient paths. As the simulation proceeded, the traffic in some road segments became congested due to the increased volume in the network, and vehicles spent more time in travelling through the congested road segments. Thus selecting the eco-path calculated by the dynamic en-route eco-navigation is able to save both fuel and time since the equipped vehicles may effectively avoid the most congested road segments. This is the major reason that both travel times and fuel consumption got improved for vehicles spawned in the second half of simulation period (generally later than 2200s), as depicted in Fig. 4.

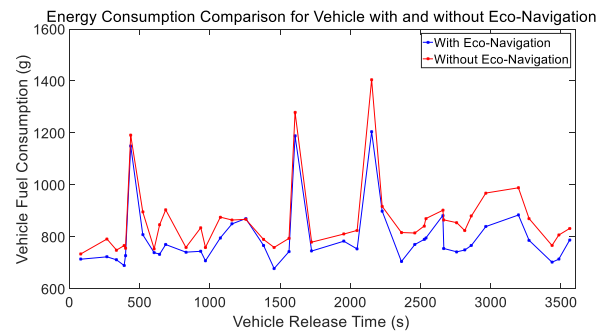


Figure 3. Energy consumption comparison for vehicle with and without eco-navigation

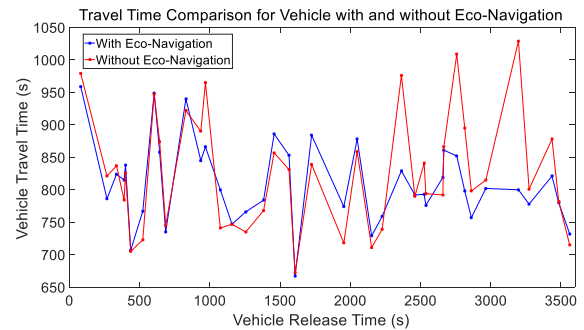


Figure 4. Travel time comparison for vehicle with and without eco-navigation

Statistical results of energy savings and travel time changes when applying dynamic en-route eco-navigation are illustrated with boxplots in Fig. 5. Basic statistics (mean, variance and median) are presented in TABLE III.

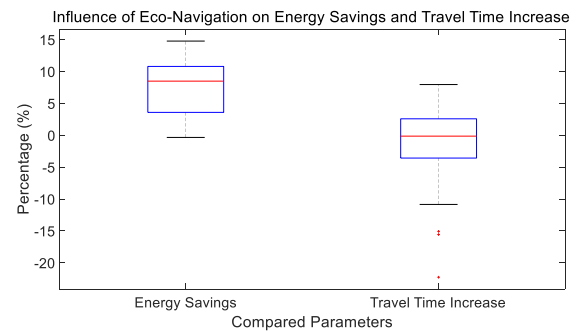


Figure 5. Energy savings and travel time increase of eco-navigation

TABLE III. STATISTICAL RESULTS ON MEASUREMENTS OF EFFECTIVENESS (MOEs) FOR DYNAMIC EN-ROUTE ECO-NAVIGATION

Statistics	Energy savings (%)	Travel time increase (%)
Mean	7.67	1.37
Variance	4.22	6.35
Median	8.50	-0.13

In addition to the basic statistics of changes in vehicle energy consumption and travel time, statistical tests were further conducted to compare the before-and-after datasets of energy consumption and travel time. Normality assumption check was first carried out and it turns out that two energy consumption datasets satisfied the assumption while the travel



time datasets did not. Therefore, a pair-wise t-test was applied to the energy consumption datasets and a K-S test (Kolmogorov-Smirnov test) was applied to the travel time datasets, and the results were presented in TABLE IV. Results show that energy savings for vehicles with dynamic en-route eco-navigation are statistically significant, while no strong evidence was found to distinguish travel times of vehicles with navigation from those without navigation.

TABLE IV. T-TEST AND K-S TEST RESULTS FOR DATASETS OF VEHICLES WITH AND WITHOUT EN-ROUTE ECO-NAVIGATION

Dataset	t-test statistics	t-test p-value	K-S test statistics	K-S test p-value
Energy Consumption	1	0.0239	--	--
Travel Time	--	--	0	0.7237

#### IV. CONCLUSIONS AND FUTURE WORK

This research focuses on the development and evaluation of dynamic en-route eco-navigation, which is aimed at reducing vehicle energy consumption and emissions by searching for the environmentally-friendly path and improving navigation efficiency. Considering microscopic vehicle energy consumption or emission information and traffic states are usually not readily available in real world navigation, an innovative methodology using a novel mesoscopic energy consumption model in authors' previous work was proposed to explore dynamic eco-route. To evaluate the proposed methodology, a case study was then carried out in a simulation network in Beijing, in which mesoscopic traffic information could be accurately aggregated from microscopic data. The optimal paths of a randomly selected vehicle under the condition of no eco-navigation, eco-navigation without en-route changes and dynamic en-route eco-navigation were compared and it turned out the dynamic en-route eco-path was different from the time priority path and the pre-trip eco-path. In addition, vehicle's environmental and mobility performances were compared individually and statistically. Results demonstrated that en-route eco-navigation was able to update the optimal path when traffic states changed drastically, and it was beneficial for enhancing vehicle environmental performance without compromising mobility.

It is noted that the dynamic en-route eco-navigation proposed in this research is evaluated from the perspective of an individual vehicle. Evaluation of the network effects under different penetration rates will be a promising future direction. In particular, as the dynamic eco-navigation is widely deployed, the network-wide traffic condition may be greatly influenced by navigated vehicles and in turn, this will result in different en-route optimal path selections, which may further stand out the significance of en-route eco-navigation. In addition, due to the lack of data on arterial roads, the eco-navigation in this research is for Beijing expressways only. As a future step, the proposed dynamic en-route eco-navigation will be studied for more comprehensive networks including both expressways and arterials. Toward this end, energy consumption modeling, link cost calculation and new navigation strategy for arterials are also future research topics.

#### REFERENCES

- [1] Ministration of Environmental Protection of the People's Republic of China, "China Vehicle Environmental Management Annual Report", 2017. <http://dqhj.mep.gov.cn/jdchjgl/zhgldt/201706/P020170605550637870889.pdf>
- [2] Beijing Environmental Protection Bureau, 2014. "Source apportionment of particulate matter (PM) 2.5 in Beijing is officially released". <http://www.bjepb.gov.cn/bjhrb/xxgk/jgzj/jjgigszjzz/xcyj/xwfb/607219/index.html>
- [3] U.S. Environmental Protection Agency, 2017. Inventory of U.S. greenhouse gas emissions and sinks: 1990 - 2015, EPA 430-P-17-001, April.
- [4] Barth, M., K. Boriboonsomsin, A. Vu. Environmentally-friendly navigation. IEEE Intelligent Transportation Systems Conference. IEEE, 2007. pp. 684-689.
- [5] Ahn, K., H.A. Rakha. The effects of route choice decisions on vehicle energy consumption and emissions. Transportation Research Part D: Transport and Environment, Vol. 13, No. 3, 2008, pp. 151-167.
- [6] Ericsson, E., H. Larsson, K. Brundell-Frej. Optimizing route choice for lowest fuel consumption—potential effects of a new driver support tool. Transportation Research Part C: Emerging Technologies, Vol. 14, No. 6, 2006, pp. 369-383.
- [7] Boriboonsomsin, K., M. J. Barth, W. Zhu and A. Vu. Eco-routing navigation system based on multisource historical and real-time traffic information. IEEE Transactions on Intelligent Transportation Systems, Vol. 13, No. 4, 2012, pp. 1694-1704.
- [8] Dijkstra, E.W.. A note on two problems in connexion with graphs. Numerische mathematik, Vol. 1, No. 1, 1959, pp. 269-271.
- [9] Rakha, H. A., K. Ahn and K. Moran. Integration framework for modeling eco-routing strategies: Logic and preliminary results. International Journal of Transportation Science and Technology, Vol. 1, No. 3, 2012, pp. 259-274.
- [10] Rakha, H., K. Ahn and A. Trani. Development of VT-Micro model for estimating hot stabilized light duty vehicle and truck emissions. Transportation Research Part D: Transport and Environment, Vol. 9, No. 1, 2004, pp. 49-74.
- [11] Ahn, K. and H. A. Rakha. Network-wide impacts of eco-routing strategies: a large-scale case study. Transportation Research Part D: Transport and Environment, Vol. 25, 2013, pp. 119-130.
- [12] Zhao, Y. and A.W. Sadek. ECO-navigation route choice evaluations with a simplified, macro-model for fuel consumption and emissions estimation [C]. ITS World Congress 2014.
- [13] Los Alamos National Lab (LANL). TRANSIMS: Transportation Analysis Simulation System. Version 3.0. (LA-UR-00-1724). New Mexico: Los Alamos. 2004.
- [14] Environmental Protection Agency Office of Transportation and Air. Introduction to MOVES2010. 2010.
- [15] Sadek, A.W. and L. Guo. An Evaluation of Likely Environmental Benefits of a Time-dependent Green Routing System in the Greater Buffalo-Niagara Region [J]. Research Project Report, University at Buffalo, The State University of New York, 2011.
- [16] Kang, J., T. Ma, F. Ma and J. Huang. August. Link-based emission model for eco routing. In: 2011 11th International Conference on ITS Telecommunications (ITST), IEEE, 2011, pp. 207-212.
- [17] Davis, N., J. Lents, M. Osses, N. Nikkila and M. J. Barth. Part 3: Developing countries: development and application of an international vehicle emissions model [J]. Transportation Research Record: Journal of the Transportation Research Board, Vol. 1939, 2005, pp. 155-165.
- [18] Yao E. and Y. Song. Study on eco-route planning algorithm and environmental impact assessment. Journal of Intelligent Transportation Systems, Vol. 17, No. 1, 2013, pp. 42-53.
- [19] Li, W., G. Wu, Y. Zhang and M. J. Barth. A comparative study on data segregation for mesoscopic energy modeling. Transportation Research Part D, Vol. 50, 2017, pp. 70-82.
- [20] National Research Council, 2000. Highway capacity manual. Washington, DC.
- [21] Barth, M.J., F. An, J. Norbeck and M. Ross. Modal emissions modeling: A physical approach. Transportation Research Record: Journal of the Transportation Research Board, Vol. 1520, 1996, pp. 81-88.