

An Evaluation of Likely Environmental Benefits of a Time-dependent Green Routing System in the Greater Buffalo-Niagara Region

FINAL REPORT

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16. Abstract Currently, strategies are being examined with regard to their potential for mitigating the negative impacts of the surface transportation sector on the environment. The focus of this study is to evaluate an ITS (intelligent transportation systems)-based strategy that involves providing route guidance to travelers. The objective of this route guidance is the minimization of emissions and a reduction of or fuel consumption, as opposed to the traditional objective of minimizing travel times. Specifically, this study conducts an assessment, using a real-world case study, of the likely environmental benefits of environmentally-based route guidance (green routing). Results indicate that such routing could result in significant reductions in emissions, but that this may come at the expense of increased travel time.					
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1 Executive Summary

With worldwide concerns about energy shortage and global warming, finding methods to cut down on energy consumption and emissions from on-road transportation has become of paramount importance. Different strategies are currently being studied for their potential for mitigating the negative impacts of the surface transportation sector on the environment. The focus of this study is on an Intelligent Transportation Systems (ITS) strategy which involves providing route guidance to travelers with the objective of minimizing emissions or fuel consumption, as opposed to the traditional objective of minimizing travel times. Specifically, this study conducts a realistic assessment, using a real-world case study, of the likely environmental benefits of environmentally-based route guidance. Several features distinguish this study from previous reported research. First, the research utilizes a realistic case study of a medium-sized metropolitan area in the U.S. with a population of about 1.2 million. Second, the research applies the latest state-of-the-art models on both the transportation as well as the environmental modeling side, through the development of an integrated model combining the Transportation Analysis and Simulation System (TRANSIMS) model and the Multi-Scale MOtor Vehicle Emissions Simulator model (MOVES). Third, the integrated model is used to approximate “Green User Equilibrium”, and to investigate the impact of market penetration on the likely environmental benefits of green routing.

Results indicate that green routing could result in significant reductions in emissions, but that this naturally comes at the expense of an increased travel time. For one scenario considered, which assumed 100% of traffic is passenger cars, green routing resulted in an almost 16.7% reduction in Carbon Monoxide (CO) emission, and a corresponding 3.3% increase in travel time. The results also indicate that tangible emissions reductions are achievable at low to medium market penetration levels for green routing applications, especially when the strategy is applied in a way that intelligently targets travelers with the largest likely emissions savings. Finally, the findings seem to point that while reductions in emissions of sizeable magnitude are possible with green routing, the savings in fuel consumption appears to be more modest.

Acknowledgement

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2 Research Introduction

Today, with the continuous increase in worldwide travel demand and increased concerns about energy availability and global climate change, the search for more sustainable transportation systems has assumed national and international priority. As is well known, the transportation sector is the chief consumer of petroleum products globally and, as a result, the dominant contributing source of criteria air pollutants. Specifically, transportation in the U.S. is responsible for more than 27 percent of energy consumption and 67 percent of petroleum consumption. On the emissions side, the sector currently accounts for 82% of Carbon Monoxide (CO) emissions, 56% of Nitrogen Dioxide (NO₂), 12% of Lead (Pb), and 5% of Sulfur Dioxide (SO₂) (ERG, 2004), and thus constitutes a significant threat on public health and welfare. Moreover, within the overall transportation sector, on-road emissions are responsible for the largest portion of the total emissions, accounting for 44% of CO emissions, 33% of NO_x emissions, and 1% of particulate matters with diameters less than 10 micrometers (PM₁₀) emissions (CCCEF, 2007). It is therefore no surprise that the transportation profession is leaving no stone unturned in its search for ways to cut down on energy consumption and emissions from on-road transportation.

Different strategies are currently being studied for their potential for mitigating the negative impacts of the surface transportation sector on the environment (EPA, 2004b; Griffith, 2007; Kear & Niemeier, 2004; Missouri I/M Group, 2004). These range from sustainable land-use planning strategies, such as smart growth and transit-oriented development strategies, to strategies that involve the development of alternative fuels (e.g. hydrogen) and green vehicles (such as plug-in hybrid electric vehicles or PHEV). Moreover, recent research has clearly demonstrated that several Intelligent Transportation Systems (ITS) applications have the potential to mitigate some of the adverse environmental impacts associated with surface transportation systems (Ahn & Rakha, 2008; Manzie, Watson, & Halgamuge, 2007; Servin, Boriboonsomsin, & Barth, 2006). In fact, it could be argued that ITS applications is among the few strategies that could help conserve energy and reduce emissions in the near-term because some of the other strategies, while promising, will require a rather long time horizon for implementation. For example, reversing the urban sprawl trend that has characterized development patterns in the United States in recent decades, or transiting to a whole new infrastructure for an alternative fuel will require several decades for their full benefits to be realized.

3 Purpose and Scope

The focus of the research is to conduct a realistic assessment, using a real-world case study of a medium-sized metropolitan area, of the likely environmental benefits of an ITS strategy that involves providing route guidance to travelers based on the least emissions or lowest fuel consumption route. At the present time, motorists typically choose their routes based on minimizing their perceived total travel time or generalized cost. Until recently, the transportation profession lacked the necessary tools to determine whether the fastest route between an O-D pair were, in fact, the optimal one from an environmental (i.e. energy consumption and emissions) standpoint. With recent advances

in state-of-the-art microscopic traffic simulation models and emissions models, it is now finally possible to accurately determine the impact of route choice on regional energy consumption and emissions. For example, (Ahn & Rakha, 2008) demonstrated that emission- and energy-optimized traffic assignment can significantly reduce emissions and save energy over the traditional User Equilibrium and System Optimum assignments. Moreover, with the proliferation of vehicle telematics and GPS navigation devices, the opportunity now exists to actually implement routing strategies that explicitly consider the criteria of minimum energy consumption and emissions. Given this, there is a genuine need for a realistic evaluation of the likely benefits on a real-world, large-scale environment.

While there have been a handful of previous studies aimed at demonstrating the potential for environmental savings resulting from green routing (these are discussed later in the report), there are several unique features that distinguish the research described herein from previous studies reported in the literature. First, the research utilizes a realistic case study involving the Greater Buffalo-Niagara metropolitan region, medium-sized area with a population of about 1.2 million; most previous studies have focused on either hypothetical or much smaller networks. Second, the research applies the latest state-of-art models on both the transportation as well as the environmental modeling side. Specifically, the study integrates the TRansportation ANalysis SIMulation System (TRANSIMS) model, on the transportation side, with the Multi-Scale MOtor Vehicle Emissions Simulator model (MOVES), on the emissions modeling side. While both models are open source, very few previous studies to date have attempted to integrate them. Third, the integration of TRANSIMS and MOVES allows the two models to be run in an iterative, closed loop fashion, and provides a mechanism for approximating what may be called “Green User Equilibrium”. Approximating “green user equilibrium” is important because as more travelers opt to follow a “green route”, that route no longer becomes the “green” route and new routing strategies would thus be needed. To the best of our knowledge, none of the previous studies explicitly accounted for that phenomenon.

3.1 Summary of Project’s Specific Objectives

The specific objectives of the research can thus be summarized as follows:

- 1) To develop an integrated simulation modeling framework capable of calculating time-dependent emission production factors for road segments in the Buffalo-Niagara metropolitan area. This will be accomplished through linking the Buffalo TRANSIMS-Niagara model to MOVES2010.
- 2) To use the TRANSIMS-MOVES2010 modeling framework to estimate the likely environmental benefits to be expected from implementing lowest emission production routing in the Buffalo-Niagara metropolitan area
- 3) To assess the impact of market penetration (i.e. the percentage of drivers utilizing least emission production routing) on the likely environmental benefits of the strategy
- 4) To assess the difference in the benefits to be expected between different vehicle types (i.e. passenger car versus truck).

3.2 Report Organization

The rest of this report is structured as follows. The next section provides an introduction of previous research in support of green routing, as well as an overview of the TRANSIMS and the MOVES models used in the current work and previous attempts at their integration. The following section then describes the case study utilized in the report, and presents the details of the integrated TRANSIMS-MOVES modeling framework and the feedback procedure designed to approximate Green User Equilibrium. That section also describes the methodology followed to assess the likely environmental benefits of least-emission or green routing, and the impact of market penetration on the likely benefits. The results from the study are presented next, followed by a summary of the study's main conclusions and discussion.

4 Background

4.1 Environmentally-based Routing – A Quick Review of Previous Research

The topic of environmental impact of traffic assignment and routing has been attracting the attention of researchers since the early 1990s. Tzeng & Chen (1993) developed a nonlinear program to develop routing strategies aimed at minimizing CO emissions, and applied it to metropolitan Taipei, as a case study. However, the study was based on a simplified travel time function and CO emission. Nagurney (2000) proposed a multi-class and multi-criteria traffic network equilibrium model which included an environmental criterion. However, the study assumed a fixed amount of CO emission rate per traveler per link. Sugawara & Niemeier (2002), using average speed CO emissions factors developed by the California Air Resources Board (CARB), demonstrated that routing strategies developed explicitly based on the objective of minimizing emissions, have the potential to reduce system-wide vehicle emissions when compared to UE and SO assignments, especially under low to moderate congested conditions.

Ericsson et al. (2006) assessed the potential benefits of lowest fuel consumption routing using a database of real traffic driving patterns in the city of Lund, Sweden. In their study, Ericsson et al. calculated the fuel consumption factor (FCF) (litre/10 km) for 22 street classes, at peak and off-peak periods and for three types of vehicles. However, it could be argued that the driving environment in the US is quite different from that in Europe. Moreover, Ericsson et al.'s study did not contain an analysis of the impact of market penetration on the likely benefits. Moreover, routing was based on historical FCFs.

Ahn and Rakha (2008) studied the impact of route choice on energy consumption and emissions, and showed that the route with the shortest travel time does not always correspond to the route with the lowest fuel consumption route. Specifically their results show that though travel on faster highways saves time, the individual motorist can save energy by driving at lower speed on an arterial route with smoother traffic. Moreover,

they show that while environmentally-based routing can significantly reduce criteria pollutants (i.e. Hydro-carbons (HC), CO, and NO_x), reductions in greenhouse gases (i.e. CO₂) are less significant. However, the case study Ahn and Rakha used was limited to a single corridor in Northern Virginia, and essentially involved the choice between a freeway route and an arterial route; a more comprehensive evaluation on a realistic network is therefore warranted. Moreover, Ahn and Rakha did not use the MOVES model because the model was not available at the time their study was conducted. MOVES is currently the official emissions model endorsed by the Environmental Protection Agency (EPA).

Another notable work in this context is the Eco-Routing Navigation System being developed at the University of California (UC), Riverside (Boriboonsomsin, Barth, Zhu, & Vu, 2010). However, that work is also not based on the MOVES model, but on UC-Riverside's Comprehensive Modal Emissions Model (CMEM), which prior to MOVES was one of the few modal and instantaneous emissions models available for researchers in that field (Barth et al., 2000).

4.2 MOVES

Four typical categories of emission models could be identified from the literature. These are: (1) travel-based models such as EPA's MOBILE family of models; (2) fuel-based models which utilize fuel use data available from tax records; (3) modal & instantaneous models such as UC-Riverside's CMEM; and (4) integrated models which integrate microscopic traffic simulation and micro emission estimation models (EEA, 2000; EPA, 2004a; Rakha, 2004, 2007). Until the release of the MOVES model in 2010, EPA's MOBILE 6 was the official travel-based model used in the U.S. for emissions modeling and conformity (Qiao, Wang, & Yu, 2007). The MOBILE model, however, was designed for estimating mobile source emissions based on average operating conditions and for large geographic areas (i.e. macro-scale and meso-scale analyses). Given this, the model is not sensitive enough for project-level and microscopic emissions analyses required for green routing calculations.

In 2010, EPA released the MOVES2010 model to address the limitations of existing emissions models and to allow for more accurate project-level analysis. Though based on MOBILE, the MOVES generation of models is not merely an upgrade of MOBILE using more recent emissions data. Instead, it is brand-new software, designed from the ground up to estimate emissions at a more detailed level. MOVES utilized the Portable Emission Monitoring System (PEMS), widely acknowledged as one of the most reliable emissions measurement technologies, to collect real-world emission data as part of its data source. The model is written in Java and uses the MySQL relational database management system. Among all those significant improvements, the ability to perform operational (project-level) emission analysis makes MOVES superior over MOBILE, in that it can account for the different patterns of acceleration, cruising, and deceleration rather than just aggregate driving cycles and differences in average speed (EPA & FHWA, 2010).

Figure 1 shows the Graphic User Interface (GUI) of MOVES2010. At left hand side, the control panel is to check the settings of a MOVES project including: project scale, time span, geographic bounds, vehicle types & road types, and pollutants & process. Beside the control panel, there is a dialog containing all the inputs a MOVES project needs. Each tag at the top of the dialog needs to be specified, and then the input data will be stored in MySQL database.

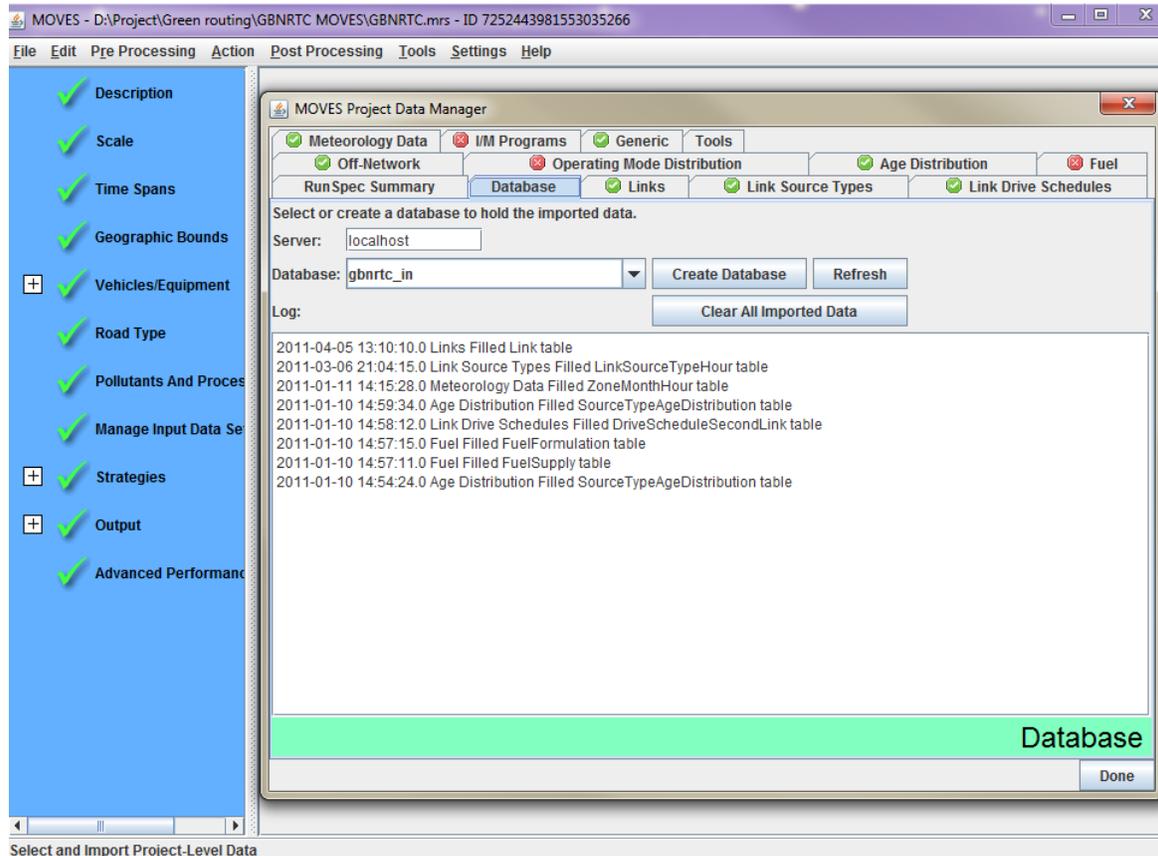


Figure 1. User Interface of MOVES2010

In terms of the “project-level” analysis, MOVES offers the user three options: (1) using the average speed approach which utilizes default MOVES driving cycles associated with the speed profile and road type; (2) using a “link drive schedule” which is a second-by-second speed profile for a given vehicle a generic vehicle representative of the driving cycle for multiple vehicles; and (3) using an operating mode approach. In this study, we adopt the second approach (i.e. the link drive schedule approach) whereby second-by-second vehicle trajectories from the traffic simulation model are used to determine the link drive schedule required for the MOVES project-level calculations.

Figure 2 shows the key required “project level” inputs using MySQL database browser.

linkID	countyID	zoneID	roadTypeID	linkLength	linkVolume	linkAvgSpeed	linkDescripti...	linkAvgGrade
11510	36029	360290	4	1.991	1	NULL		0.00187254
11511	36029	360290	4	1.991	0	NULL		-0.00187254
11530	36029	360290	4	1.65939	14	NULL		-0.150852
11531	36029	360290	4	1.65939	21	NULL		0.150852
11540	36029	360290	4	0.830028	22	NULL		0.2972
11541	36029	360290	4	0.830028	18	NULL		-0.2972
11550	36029	360290	4	0.740985	21	NULL		-0.900629
11551	36029	360290	4	0.740985	30	NULL		0.900629
11560	36029	360290	4	2.85253	27	NULL		0
11561	36029	360290	4	2.85253	21	NULL		0
11600	36029	360290	4	1.58282	8	NULL		-0.463628
11601	36029	360290	4	1.58282	5	NULL		0.463628
13340	36029	360290	5	0.429989	174	NULL		0.0289017
13341	36029	360290	5	0.429989	289	NULL		-0.0289017
13350	36029	360290	5	0.170007	211	NULL		0
13351	36029	360290	5	0.170007	310	NULL		0
13360	36029	360290	5	0.259982	537	NULL		0
13361	36029	360290	5	0.259982	320	NULL		0
17310	36029	360290	5	0.485415	434	NULL		-0.0512033
17311	36029	360290	5	0.485415	334	NULL		0.0512033
17380	36029	360290	5	0.490013	352	NULL		-0.219376
17381	36029	360290	5	0.490013	381	NULL		0.219376
17450	36029	360290	5	0.473423	658	NULL		-0.0603754

(a) The Input of Each Link's General Information

linkID	secondID	speed	grade
18381	1	10.0662	0.289941
37420	1	25.8366	0.46219
37640	1	25.7248	2.70541
38300	1	21.2509	-1.10227
38301	1	28.1854	1.10227
38590	1	24.7181	-0.724538
40051	1	11.6321	0.0847218
46560	1	12.3031	0.662722
48121	1	21.4746	0.209296
83451	1	26.8432	-0.0908113
110501	1	24.9418	-1.17875
17991	2	26.5077	0.00536625
18381	2	16.777	0.289941
19421	2	25.0537	-0.207996
31901	2	21.5864	-0.0145426
37101	2	24.9418	-0.383576
37390	2	28.9683	0.18136
37420	2	50.3311	0.46219
37601	2	27.738	-0.100764
37640	2	50.3311	2.70541
38181	2	16.6652	0.788158
38300	2	50.3311	-1.10227

(a) The Input of Each Link's Second-by-second Drive Schedule

Figure 2. Sample Inputs of MOVES Stored in MySQL Database

Chamberlin, Swanson, Talbot, Dumont, & Pesci (2011) compared the emissions calculated by both MOVES and CMEM for a signalized intersection and a roundabout, as an example of a project-level analysis. Their results show that the two models yield comparable estimates for NOx emissions but quite dissimilar results for CO estimates. According to the researchers this may be attributed to the fact that CMEM analytically models the physical processes associated with combustion, whereas MOVES model uses a statistical modeling approach for grouped vehicle speeds. Chamberlin et al. also

recommend that future research should address more complex networks and should investigate methods for automating the connection between micro-simulation model outputs and MOVES link drive schedule. We specifically address those two recommendations in our current report.

4.3 TRANSIMS

TRANSIMS, initially developed by the Los Alamos National Lab (LANL), is an agent-based transportation model which allows for simulating and tracking travel on a person-by-person and second-by-second basis. The model was envisioned by the Federal Highway Administration (FHWA) as representing the “next generation” of transportation planning models, and was designed to provide transportation planners with increased policy sensitivity, more accurate emission estimates (when linked to a microscopic emissions model such as MOVES or CMEM), and powerful visualization capabilities.

TRANSIMS has four major functional components: (1) a population synthesizer; (2) an activity demand generator; (3) an intermodal route planner or router; and (4) a regional micro-simulator, which uses a cellular automata (CA) model to estimate second-by-second vehicle positions and speeds typically defined by a 7.5-meter cell locations. A report conducted by (Williams, Thayer, & Smith, 1999) proved that the coarse-grained 7.5 meter per second velocity bins was good enough for obtaining the representation of actual emissions, even under the circumstances that the challenging enrichment (hard acceleration mode) occurs. The TRANSIMS model allows for multi-scale modeling in the sense that one part of a transportation network could be modeled in great detail in the micro-simulator, whereas the remaining area could be modeled to a lesser degree of detail in Router which models link travel time using the Public Roads Bureau famous formula.

From its inception, the ability to use TRANSIMS for more accurate emission calculations was at the forefront of FHWA’s thinking. In fact, the model was applied to estimate emissions for case studies in New Mexico and Houston, TX (Zietsman & Rilett, 2001). However, the original emissions module developed to be used within TRANSIMS was based on crude models which are obviously obsolete compared to EPA’s state-of-the-art MOVES2010. The integrated modeling framework of TRANSIMS and MOVES presented in this report thus provides a much more powerful microscopic tool for analyzing traffic operation impact on emissions.

4.4 Integrated Simulation-Emissions Models using MOVES

Because MOVES is a relatively new model (released by EPA in 2010), the integration between MOVES and traffic simulation models is still very limited so far. Besides our integrated model, only one other study, involving integrating MOVES and the DynusT (Dynamic Urban Systems in Transportation) transportation simulation model, could be found in the literature (Lin, Yi-Chang, Vallamsundar, & Song, 2011). In their work, Lin et al. (2011) used the operating mode distribution approach for microscopic emissions analysis using MOVES, whereas we use the link drive schedule approach. In addition, our case study covers a much larger transportation network.

4.5 The Buffalo-Niagara Metropolitan Area Case Study

As previously mentioned, in this study, we evaluate the likely environmental benefits of green or least emissions routing using the real-world Greater Buffalo-Niagara metropolitan region transportation network as a case study. A few years ago, the Buffalo-Niagara area was selected as one among a handful sites nationwide for the test deployment of the TRANSIMS model, focusing on freight border-crossing issues. That study, which was completed by Volpe National Transportation Systems Center in 2008, implemented the Router model for the whole area, but only used Micro-simulator to simulate a rather small region (i.e. sub-area) in great detail that was deemed crucial to understanding the freight border-crossing issues which were the focus of that study. Two years ago, the University at Buffalo (UB) received funding from FHWA to conduct a follow-up study on the initial TRANSIMS deployment aimed, among other things, at extending the scope of the area modeled in micro-simulator and further calibrating the model.

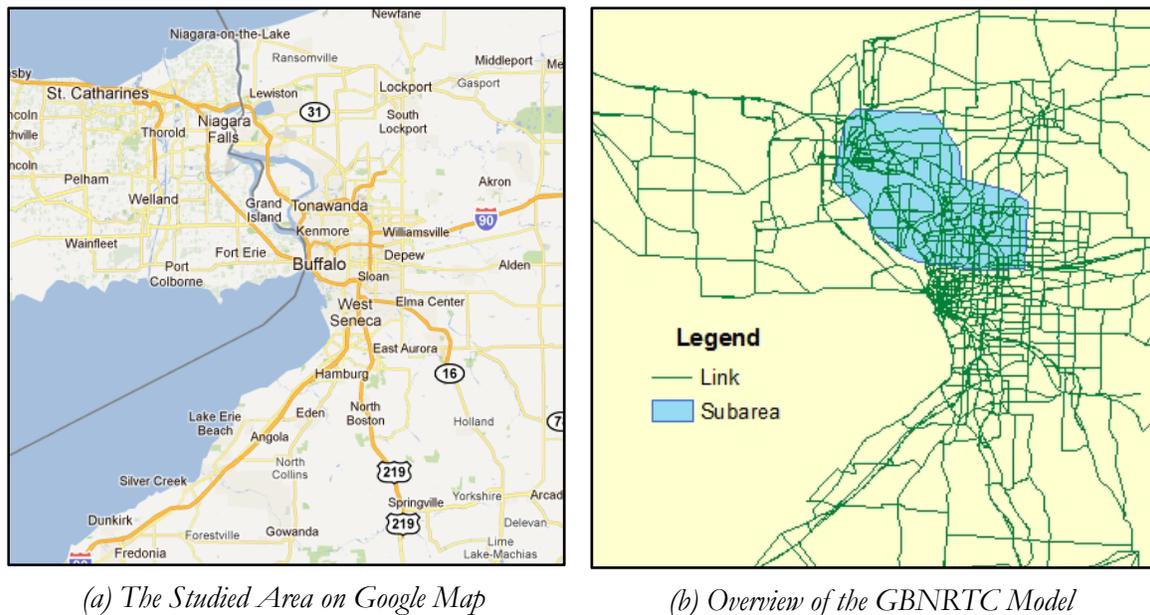


Figure 3. Case Study Network

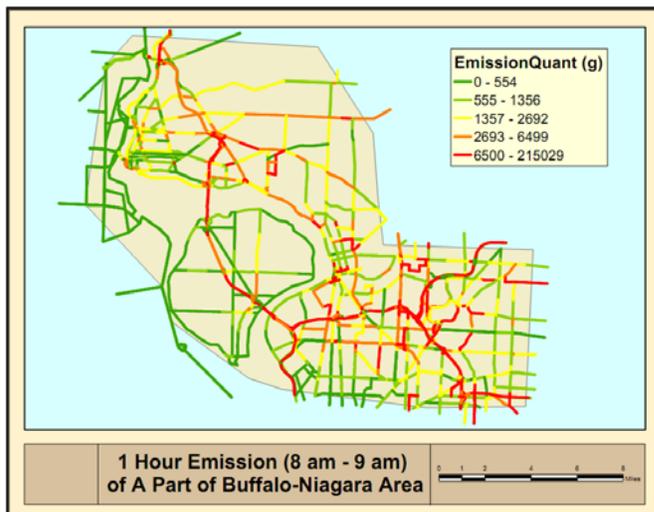
Figure 3 shows both the extent of the full Buffalo-Niagara transportation network, and the extent of the subarea (shaded in light blue) which is modeled in great detail in TRANSIMS micro-simulator at the current time. Overall, the full Buffalo-Niagara network has a total of 7,798 road links, whereas the subarea network includes a total of 2,605 links. Given that detailed second-by-second vehicle trajectories are only available from the micro-simulator output (and not from Router which uses an aggregate macroscopic traffic modeling approach), what this means in terms of emissions modeling is that the detailed MOVES link drive schedule approach for emissions modeling could be applied only to those links lying within the shaded subarea (i.e. a total of 2,605 links).

For the remaining 5,193 links, MOVES average speed approach is utilized to calculate the emissions.

While the Buffalo-Niagara TRANSIMS model tracks travel throughout the full 24-hour daily period, we limit our attention in this case study to the 8:00 – 9:00 AM time period. Moreover, when calculating the likely benefits of green routing, we limit the emissions calculations to emissions on those links contained within the shaded subarea which is modeled in great detail in the micro-simulator, since emissions calculations for the other links (i.e. those outside the subarea) are only based on the average speed link approach and hence is rather crude. Nevertheless, we consider all four types of trips which could possibly use the subarea road links, namely: (1) trips with both origins and destinations contained within the subarea (a total of 101,775 trips during the 8 to 9 am time slot); (2) trips originating within the subarea with destinations outside it (a total of 41,143 trips); (3) trips with origins outside the subarea but with destinations within the area (a total of 43,057 trips); and (4) trips passing through the subarea (a total of 7,461 trips).

For emissions, we focus in this study on Carbon Monoxide (CO) and nitrogen oxides (NO_x) as the pollutants of interest, given that EPA has approved MOVES2010 as the official model for quantitative CO and NO_x analyses for transportation conformity (OTAQ, 2010). We also consider two vehicle types: passenger car and long haul truck at the moment.

Figure 4 shows output of first iteration of the TRANSIMS-MOVES model. Map (a) shows one hour aggregated emission produced by each link based on shortest path routing strategy at the condition of user equilibrium. Table (b) shows the normalized the time-dependent EPF of each link which is going to be fed back to TRANSIMS for new routing.



(a) The Emission Production of Study Area on Esri ArcMap

A	B	C	D	E	F
LINK	DIR	START TIME	END TIME	USE	EPF (g/veh/link)
1153	0	28800	32400	ANY	9.98
1153	1	28800	32400	ANY	10.3
1154	0	28800	32400	ANY	10.09
1154	1	28800	32400	ANY	9.8
1155	0	28800	32400	ANY	8.81
1155	1	28800	32400	ANY	9.96
1156	0	28800	32400	ANY	9.18
1156	1	28800	32400	ANY	8.95
1160	0	28800	32400	ANY	9.07
1160	1	28800	32400	ANY	9.29
1334	0	28800	32400	ANY	7.06
1334	1	28800	32400	ANY	8.29
1335	0	28800	32400	ANY	11.97
1335	1	28800	32400	ANY	11.8
1336	0	28800	32400	ANY	9.99
1336	1	28800	32400	ANY	9.5
1731	0	28800	32400	ANY	9.41

(b) The Emission Production Factor Table of Study Area

Figure 4. Emission Production of Each Link in Subarea Network vs. the Generated Emission Production Factor Table for Green Routing

5 Methodology

5.1 The Integrated Modeling Framework

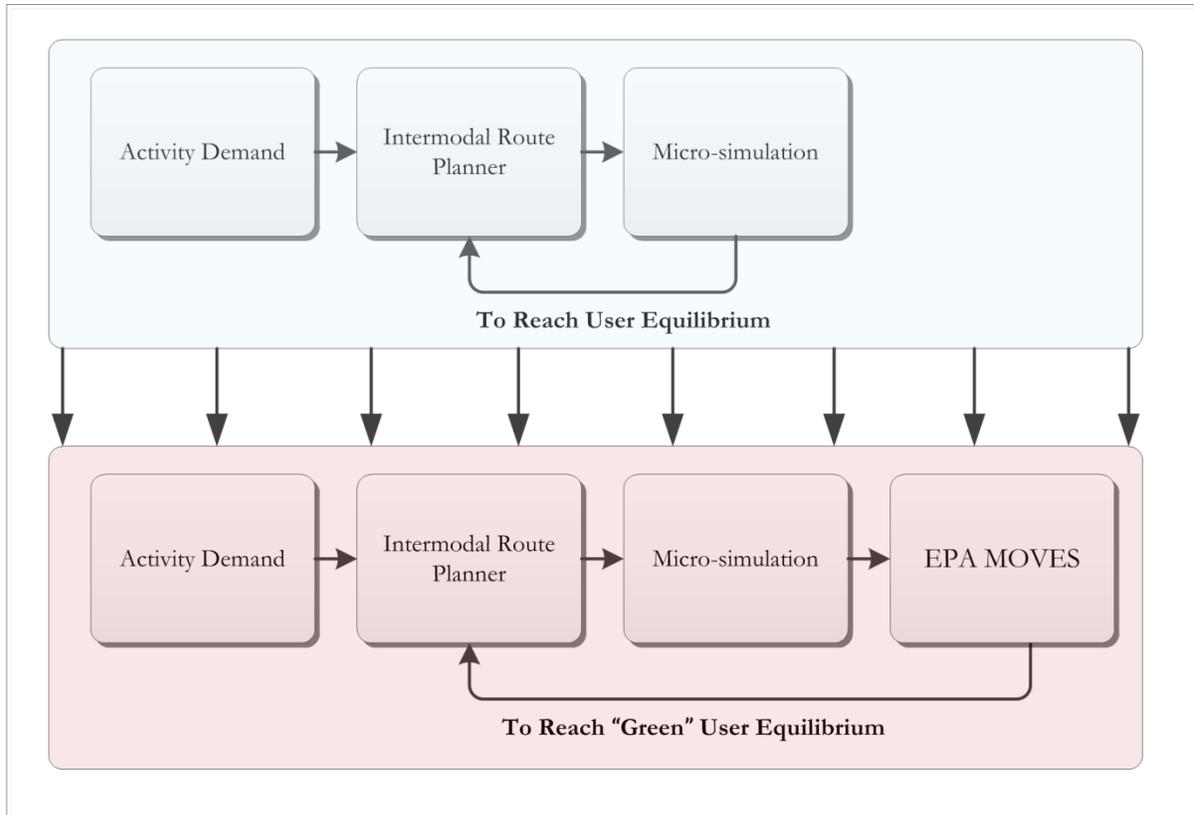


Figure 5. Transformation from the Original TRANSIMS Framework to the Integrated MOVES Framework

The logic of our integrated modeling framework is graphically shown on Figure 5, which compares the stand-alone TRANSIMS modeling framework (the upper half of Figure 5) with our integrated TRANSIMS-MOVES approach (the lower half of Figure 5). In a typical stand-alone TRANSIMS application, there is a feedback loop between the Route Planner or Router module and the micro-simulator in order to approximate user equilibrium, as shown in Figure 5. In that loop, Router first calculates the shortest paths for the different trips based first on aggregate travel time estimates. Those paths are then passed onto the micro-simulator which simulates the resulting traffic dynamics using its cellular automata model. As a result of the micro-simulator run therefore more accurate estimates of link travel times become available. Those travel times are thus fed back into Router which calculates new shortest paths for the trips based on the micro-simulator determined travel times. This process is repeated until user equilibrium is approximately reached.

Compared to the stand-alone TRANSIMS approach, our integrated modeling framework takes the output from TRANSIMS micro-simulator (i.e. the second-by-second vehicle speed trajectories) and feeds that into EPA MOVES model for the purpose of calculating the link-based emissions and/or fuel consumption, using the link drive schedule approach. This results in calculating link-based emissions production factors as is described later in the report. The link-based emissions production factors are then fed back into Router, which would then calculate new routes, this time using the emissions criterion instead of the links' travel time.

5.2 The Details of Linking TRANSIMS with MOVES

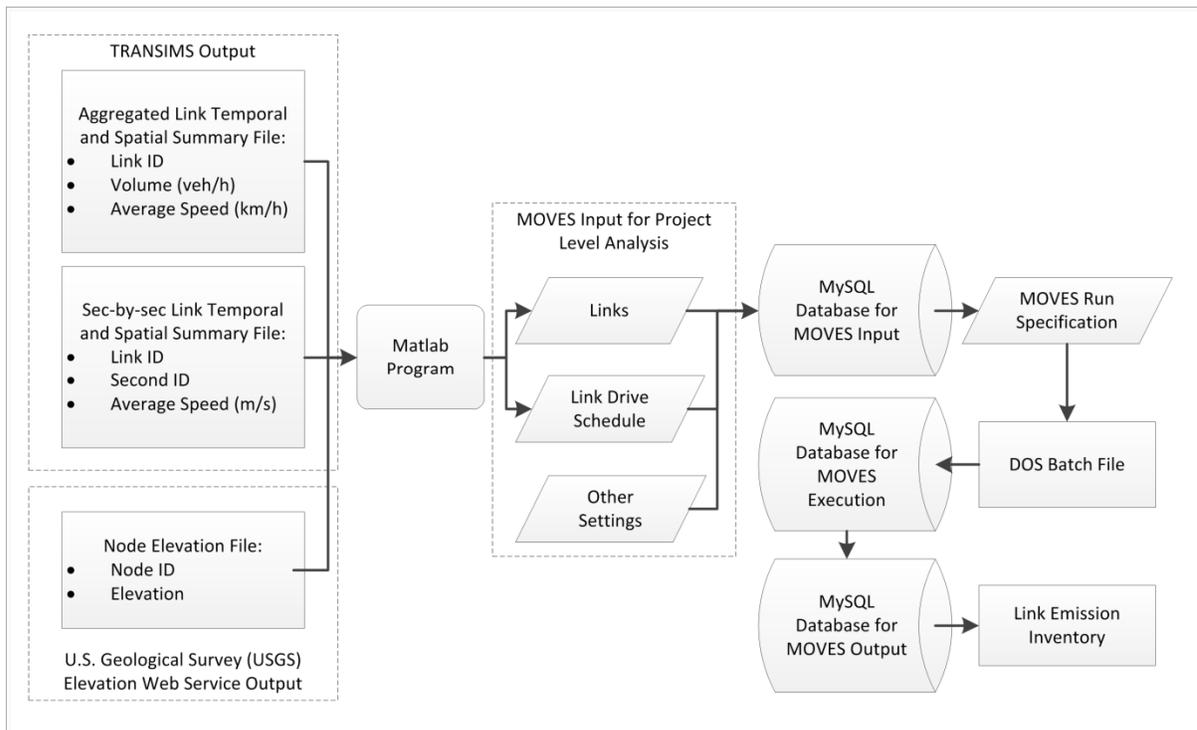


Figure 6. Linking TRANSIMS with MOVES

Figure 6 shows the details of linking TRANSIMS with MOVES. Given the size of the network considered in this study, an automated procedure for extracting the output from TRANSIMS, converting it into the format required by MOVES, running the MOVES model, and then extracting the output from MOVES and feeding it back to the TRANSIMS Router was needed. That automated procedure was also essential to allow for running the TRANSIMS and MOVES model in an iterative, closed loop fashion in order to approximate green user equilibrium. To accomplish this, a Matlab program was developed as shown in

Figure 6 to take TRANSIMS output and put it in the format required by MOVES. As can be seen, for those links within the subarea, the detailed second-by-second vehicle speed trajectories are used to derive the link drive schedules. Specifically, the average speed in

meters per second of the vehicles using the link during each time increment (i.e., one second in our case study) was first calculated, and the sequence of those second-by-second speeds was regarded as a “typical vehicle” speed trajectory or drive schedule for that link. The Link Drive Schedules, calculated from the TRANSIMS output, are then internally converted within MOVES into operation mode distributions, and used to calculate the emissions on each link. For those links outside the micro-simulated area, the Matlab program extracts the average link speed and volume and passes those onto MOVES for calculating the emissions based on the average speed approach.

The screenshot shows the USGS GISDATA Map Studio interface. On the left is a navigation menu with options like 'Interactive Maps', 'Data Delivery', and 'Map Services'. The main content area is titled 'Elevation Query Web Service Overview' and contains descriptive text and a 'Methods List' with links for 'getElevation' and 'getAllElevation'. Below this is an 'Elevation Query WSDL' link and an 'Elevation Query Direct Link'. On the right side, a table displays the results of the elevation query for various nodes. The table has columns labeled A through E, with A being 'NODE', B 'X_COORD', C 'Y_COORD', D 'Z_COORD', and E 'NOTES'. A red vertical box highlights the 'Z_COORD' column. Row 23 is highlighted in yellow.

	A	B	C	D	E
1	NODE	X_COORD	Y_COORD	Z_COORD	NOTES
2	701	168680.7	4769273	171.78	External Node
3	702	169108.7	4776230	177.87	Subarea Node
4	703	169092.7	4784342	181.84	Subarea Node
5	705	166073.3	4782822	193.65	External Node
6	1078	182403.1	4763900	183.64	Subarea Node
7	1221	183544.6	4761519	182.74	External Node
8	1223	184440.6	4761488	184.75	External Node
9	1225	185421	4761520	187.25	External Node
10	1226	185819.2	4761402	188.85	External Node
11	1230	186865.3	4761351	194.72	External Node
12	1233	181238.4	4761764	183.41	External Node
13	1235	181783.3	4761869	181.27	External Node
14	1236	182538.7	4762162	182.11	External Node
15	1237	183117.2	4762333	182.34	Subarea Node
16	1238	183597.3	4762298	182.34	Subarea Node
17	1239	184118.4	4762286	182.79	Subarea Node
18	1240	184417	4762273	183.02	Subarea Node
19	1241	185060.7	4762253	186.15	Subarea Node
20	1242	185196	4762247	186.79	Subarea Node
21	1243	185940.7	4762216	186.75	Subarea Node
22	1245	187090.6	4762151	188.63	Subarea Node
23	1246	187398.9	4761959	194.15	Subarea Node
24	1248	181206.4	4762212	176.21	External Node

Figure 7. Calling USGS Elevation Query Web Service to Obtain the Elevations of All Nodes of GBNRTC Network

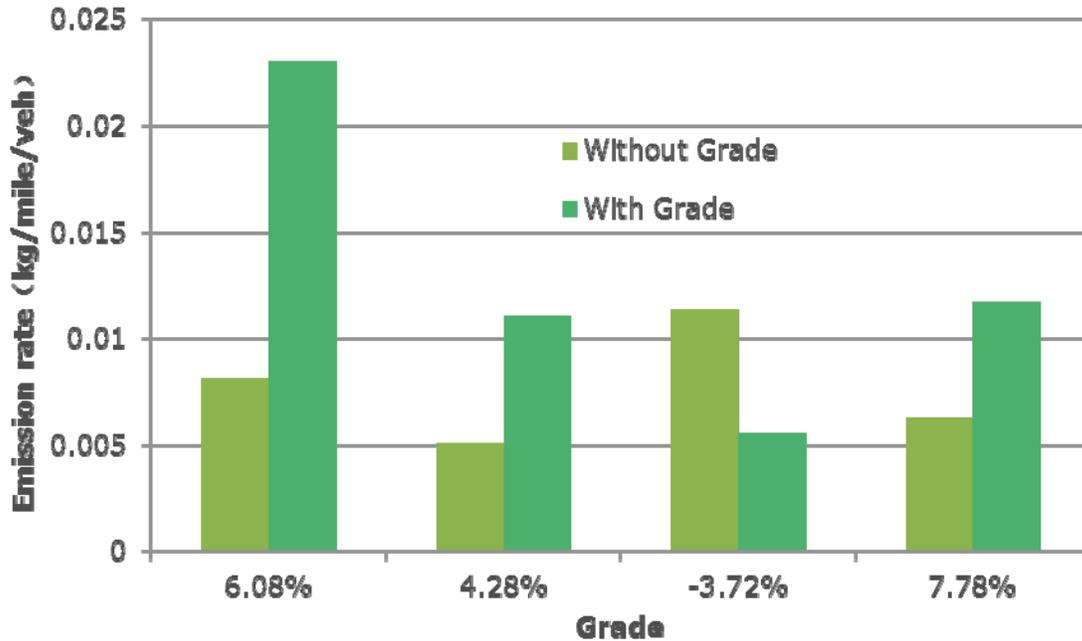


Figure 8. Four Links’ Sample Experiment for Testing the Impacts of Gradient on Emission Production

It is worth mentioning here that the original Buffalo-Niagara TRANSIMS model lacked the gradient information of the modeled roadways. Given the significant impact that roadway grade has on emissions and fuel consumption (e.g. Park & Rakha (2006) show that vehicle fuel consumption and emissions rates increase by more than 9% for a 1% increase in roadway grade), another program was developed to extract the elevation of the nodes of each link through the U.S. Geological Survey (USGS) Elevation Web Service, which is shown in Figure 7. Based on this, the link gradients were computed and together with other required input data incorporated into the corresponding fields of MySQL tables for the MOVES input database. This is also shown on Figure 6. Other settings for running the MOVES model included: (1) specifying the 8:00 – 9:00 AM time period on weekdays in October, 2006 as the analysis time period of interest; (2) specifying exhaust carbon monoxide (CO) / nitrogen oxides (NO_x) as the target process and pollutant; and (3) setting gasoline - passenger cars/ long haul truck as the on road vehicle equipment.

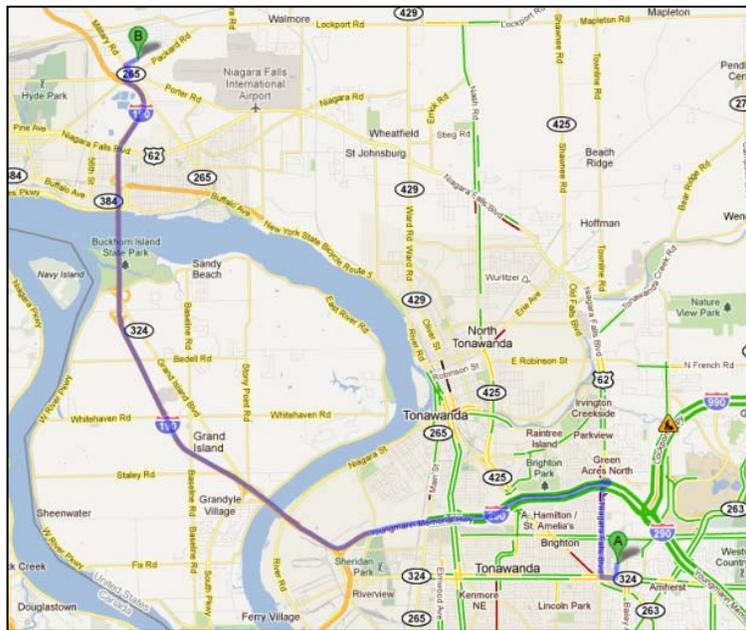
5.3 Emission Production Factor and Green Routing Traffic Assignment

Following the calculation of the link emissions inventory from MOVES (as shown in Figure 6), an Emission Production Factor (EPF) is calculated for each link. The EPF for a given link α , and which forms the basis for the green route calculations as explained below, is calculated as shown in Equation 1 below:

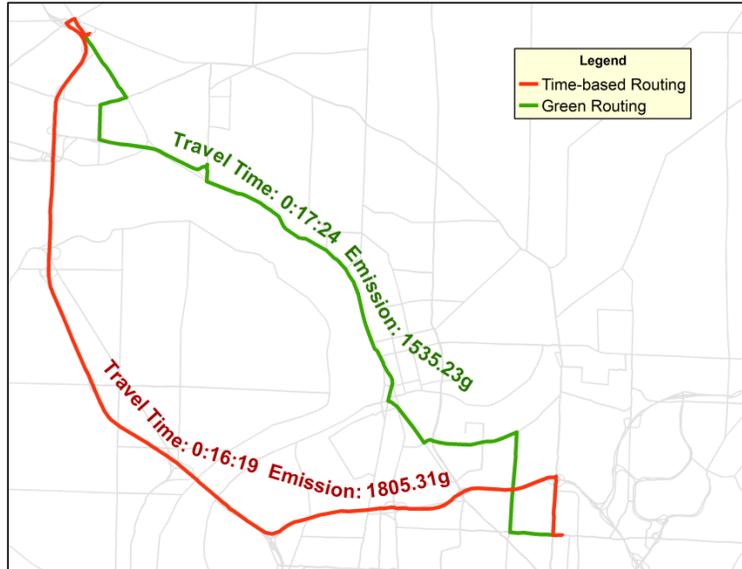
$$EPF_{\alpha} = \frac{Emission\ Quantity_{\alpha}}{Volume_{\alpha}} \quad \text{Equation (1)}$$

where

$Emission\ Quantity_{\alpha}$ represents the one-hour pollutant quantity produced by all vehicles through link α ; and $Volume_{\alpha}$ represents the one-hour flow rate or volume on link α . The emission-optimized or green assignment is then implemented by regarding the link-based EPF as the measurement of a link's travel cost instead of travel time or monetary expenses. Specifically, we feed the computed EPF back to TRANSIMS Route Planner (Router) whose settings of generalized cost function have been modified to only use the user-supplied EPF as the travel cost expression, and let Router prepare the trip plans for all travelers based on EPF. In this way, the individual traveler will switch their choice from the fastest route to the lowest pollutant emissions route, if the two routes were different. The green routing assignment is then simulated within the TRANSIMS Micro-simulator, and a second run of the MOVES model is executed to calculate the difference in emissions between the shortest travel time assignment and the least emissions assignment.



(a) The Google Map Routing Result



(b) Time-based Routing vs. Green Routing

Figure 9. Example Comparison of Individual Route Choice under UE Assignment and Green Routing Assignment

Figure 9 is included herein to show the differences between least emissions and shortest travel time assignments for an individual traveler whose origin and destination are both located within the subarea. In the figure, the red route (the shortest travel time route) went through the faster interstate highway I90; this was consistent with the fastest route provided by the Google Map service. It consumes less travel time while producing larger pollutant emission, compared with the green route which travels along a parallel arterial. Specifically, for that individual driver, green routing results in about 15% reduction in CO emission, but this comes at the expense of about 6.6% increase in travel time.

5.4 Feedback Design for Green Routing Procedure

The previous section has described how the TRANSIMS and MOVES models were linked to implement a single iteration of green routing assignment based on EPF. However, the above procedure does not take into account the fact that as more travelers choose to follow what was initially judged to constitute the green route, that route no longer becomes the greenest route because of the resulting congestion with many travelers switching to that route from other less green ones. To address this, a feedback procedure was designed to let TRANSIMS and MOVES work in an iterative loop to equilibrate the assigned traffic in the network until a new equilibrium is achieved. In this context, we define the equilibrium under green routing assignment as Green UE. Figure 10 illustrates how the feedback for Green UE works.

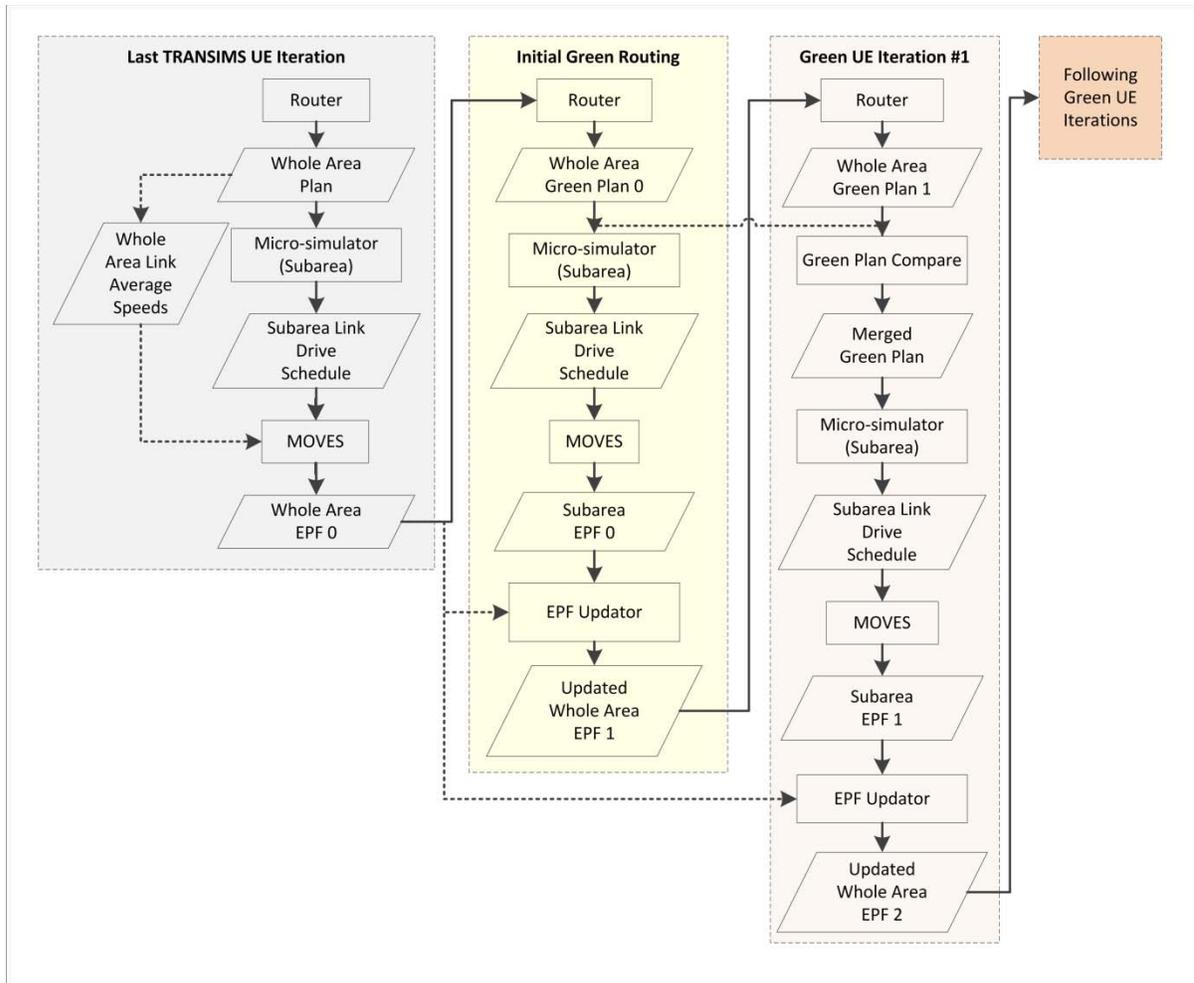


Figure 10. Feedback Design for Green UE

After running the initial iteration of the combined TRANSIMS – MOVES model as described in the previous section (this is represented by the left flow chart (i.e. the last stand-alone TRANSIMS UE iteration) and the middle flow chart (i.e. the initial green routing iteration

Figure 10), the EPFs calculated for the whole area are fed back into TRANSIMS Router. Router then uses these as its new weights for preparing the routing plans for all travelers (we are now in Green UE iteration #1). At this point, the new routing plans are compared with the plans from the previous iteration, in terms of their emission reductions, using a program which we developed specifically for this purpose called “Green Plan Compare”. The “Green Plan Compare” calculates and compares each individual vehicle’ emission according to the link chains before and after EPFs’ update, and only allows the plans that improved the emission savings to replace the old ones in the plan file which is to be micro-simulated again. Even though some travelers’ plans may have not changed in-between iterations, their interactions with rerouted travelers differ, and the resulting emissions from both sets of travelers change. Continuing this iteration process, green routing assignment is adjusted until each individual traveler take their optimal route for

producing lowest emissions given that all the other travelers are attempting to do exactly the same. In this manner, green UE routing is approximated.

5.5 Market Penetration of Green Routing Users

This part of the study aimed to understand the impact of market penetration of green routing users (i.e. the percentage of travelers who follow a green routing type of assignment) on the likely environmental benefits of green routing in terms of total system emissions reductions and the corresponding expected increase in travel time.

Figure 11 shows how the market penetration procedure works. After obtaining the assignment results of UE and Green UE, a list of travelers, corresponding to a given market penetration rate (e.g. 10%, 20%, etc.) is provided to Router. The selected travelers are then rerouted based on the computed EPFs out of the Green UE assignment. The remaining travelers, on the other hand, continue to follow their original plans based on the shortest travel time UE assignment. The two sets of plans are then merged and simulated by the micro-simulator, which reflects the interaction between the green routing users and the least travel time routing travelers. The resulting emissions for the subarea are then calculated. Two types of market penetration evaluations were conducted based on how the fraction of travelers following green routing is determined (i.e. in a random or in an intelligent way) as described below.

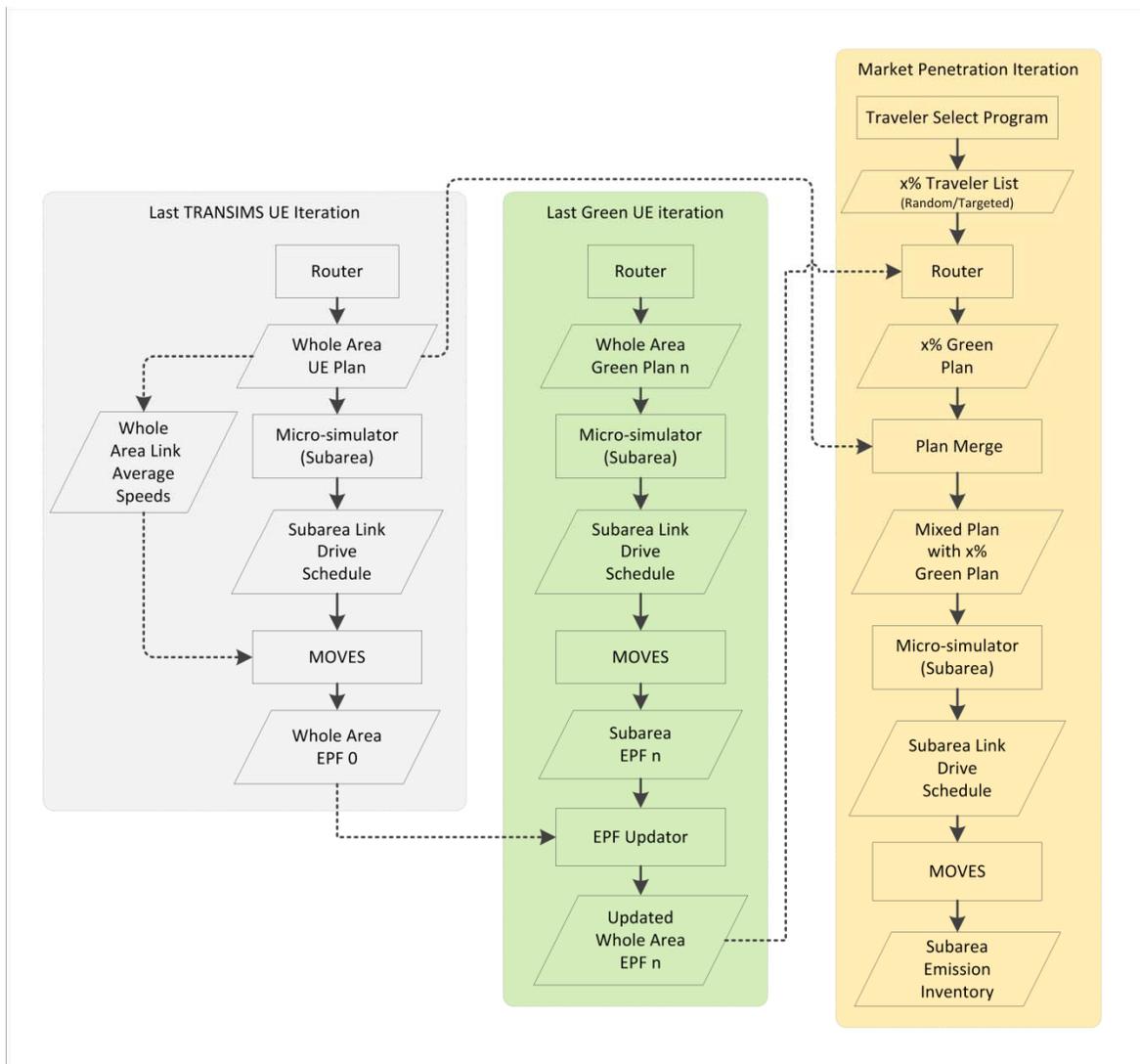


Figure 11. Market Penetration of Green Routing Users

5.5.1 Random market penetration

The assumption of this approach is that the travelers who choose to use the green routing guidance system are randomly distributed in the study area. In this model, the randomly permuted travelers are proportionally selected to form the traveler list for re-routing.

5.5.2 Targeted market penetration

The assumption of this approach is that advanced ITS technology is available to support real-time vehicle-to-infrastructure communication, and that the travelers who have the greatest potential for emissions reductions are led to take the green routes to their destinations (Yu, Jia, Qiao, & Qi, 2008). Compared with the random market penetration, instead of randomly permuting the traveler list, the researchers intelligently select candidate travelers for green routing (e.g., by sorting by individual vehicle's emission reduction in a descending manner and selecting the travelers from the top).

6 Results and Analyses

In this study, the integrated green routing system utilizing TRANSIMS and MOVES is deployed and run on a Dell OptiPlex 765 Desktop PC with an Intel® Core™2 Duo E8400 3GHz processor, 4GB memory, and 500GB 7200rpm Hard Drive. Software installed on the PC includes Windows 7 Professional, MySQL Server 5.1, MOVES 20100826, TRANSIMS 4.0.8, and MathWorks Matlab 2010b.

6.1 Green User Equilibrium Results

The stand-alone GBNRTC TRANSIMS model was first run for 25 iterations to reach a stabilized travel-time based UE status. After that, an initial iteration of the integrated TRANSIMS-MOVES model was run, followed by ten subsequent iterations designed to approximate green UE. The run time for the initial integrated model iteration was approximately 40 hours, whereas the average run time for each of the following iterations was in the order of 5 hours/iteration.

The detailed results of Green UE with different settings are shown in Tables 1 through 4. The proposed GUE has greatly reduced the total CO emission for both passenger cars and long haul trucks, from respectively the 2,220.73kg and 6453.50 in the beginning, to a range between 1,814.45kg and 1878.03kg for passenger cars and a range between 5,208.24kg and 5277.24kg for long haul trucks. The corresponding emission reduction rate is between 16.77% and 18.65%. This results together with passenger cars' NOx emission in Table 1 indicates that the green routing assignment could bring in significant reductions in pollutant emissions. Secondly, it can be seen that the reductions in emissions or fuel consumption naturally comes at the expense of increased travel times. According to Tables 1 through 4, the average travel time in the subarea increased by 3.33%, 11.04%, 12.70% and 2.46% respectively in four different assignments. Nevertheless, it can be seen that one may be able to strike a good balance between emissions reductions and travel time increase. Specifically, for Green UE assignment considered, green routing resulted in an almost 16.77% reduction in passenger car CO emission, and in a corresponding increase in average travel time of only 3.33%, which means that the reduction in emissions was almost 4 times the corresponding increase in travel time. It is to be noted that the slight oscillations in the resulting subarea-wide emissions and travel time may be attributed to the fact that the emissions and travel time calculations are based on the sub-area whereas the routing itself considers the full Buffalo-Niagara region.

The use of the subarea leads to another complexity. Because emissions are calculated differently for the micro-simulated subarea and for areas outside the micro-simulator, we have found that some trips tend to go outside the subarea (i.e. avoid travel within the subarea where emissions are calculated more accurately) so as to minimize emissions. This effect however did not appear to be realistic, but seems to be rather a byproduct of having only a subarea modeled in micro-simulator and the rest in Router.

To address this issue, our preliminary results therefore are computed based on those travelers who make their trips only within the subarea no matter using any strategy. There are 28772 out of 51706 such internal travelers involved in the summarized computation. Since the considered number of travelers are only a subset of all green routing travelers, the significance of effects of green routing is somewhat weakened. We plan to address this in our future research.

Nevertheless, the preliminary results should be indicative of the promise of green routing to significantly reduce emissions and fuel consumption (although the expected percent reduction in fuel consumption is lower than that for emissions).

Table 1. Green UE Results Based on the Passenger Cars' CO Emission

Iteration ID	CO (kg)	Average Travel Time (min)
Shortest Path	2220.73	5.67
Green Routing #1	1824.42	5.83
Green Routing #2	1878.03	5.73
Green Routing #3	1830.50	5.84
Green Routing #4	1862.30	5.93
Green Routing #5	1837.82	5.98
Green Routing #6	1862.15	5.79
Green Routing #7	1843.64	5.84
Green Routing #8	1859.65	5.94
Green Routing #9	1814.45	5.87
Green Routing #10	1870.17	5.84
Average Variation (compared with shortest path)	16.77%	3.33%

Table 2. Green UE Results Based on the Passenger Cars' NOx Emission

Iteration ID	NO _x (kg)	Average Travel Time (min)
Shortest Path	264.49	5.67
Green Routing #1	206.84	5.78
Green Routing #2	215.76	6.31
Green Routing #3	209.60	6.56
Green Routing #4	218.97	6.47
Green Routing #5	217.61	6.44
Green Routing #6	208.20	5.96
Green Routing #7	219.22	6.52
Green Routing #8	207.46	5.80
Green Routing #9	215.06	6.53
Green Routing #10	211.21	6.59
Average Variation (compared with shortest path)	19.47%	11.04%

Table 3. Green UE Results Based on the Passenger Cars' Gasoline Consumption

Iteration ID	Gasoline (gallon)	Average Travel Time (min)
Shortest Path	9682.96	5.67
Green Routing #1	9149.23	6.27
Green Routing #2	9081.53	6.17
Green Routing #3	9151.71	6.47
Green Routing #4	9150.03	6.33
Green Routing #5	9170.51	6.48
Green Routing #6	9147.63	6.39
Green Routing #7	9148.53	6.45
Green Routing #8	9143.38	6.32
Green Routing #9	9163.07	6.40
Green Routing #10	9135.70	6.62
Average Variation (compared with shortest path)	5.55%	12.70%

Table 4. Green UE Results Based on the Long Haul Trucks' CO Emission

Iteration ID	CO (kg)	Average Travel Time (min)
Shortest Path	6453.50	5.67
Green Routing #1	5235.32	5.81
Green Routing #2	5281.30	5.63
Green Routing #3	5233.12	5.90
Green Routing #4	5277.24	5.69
Green Routing #5	5208.24	5.85
Green Routing #6	5271.47	5.80
Green Routing #7	5251.72	5.76
Green Routing #8	5247.39	5.94
Green Routing #9	5246.78	5.87
Green Routing #10	5246.78	5.84
Average Variation (compared with shortest path)	18.65%	2.46%

Figure 12 summarizes the results from the aforementioned tables. As can be seen, with green routing, pollutants can be greatly reduced, and that comes at the expense of a small increase in travel time. Also as can be seen from the Figure, the saving in fuel consumption are rather modest (around 5%), compared to reductions in emissions.

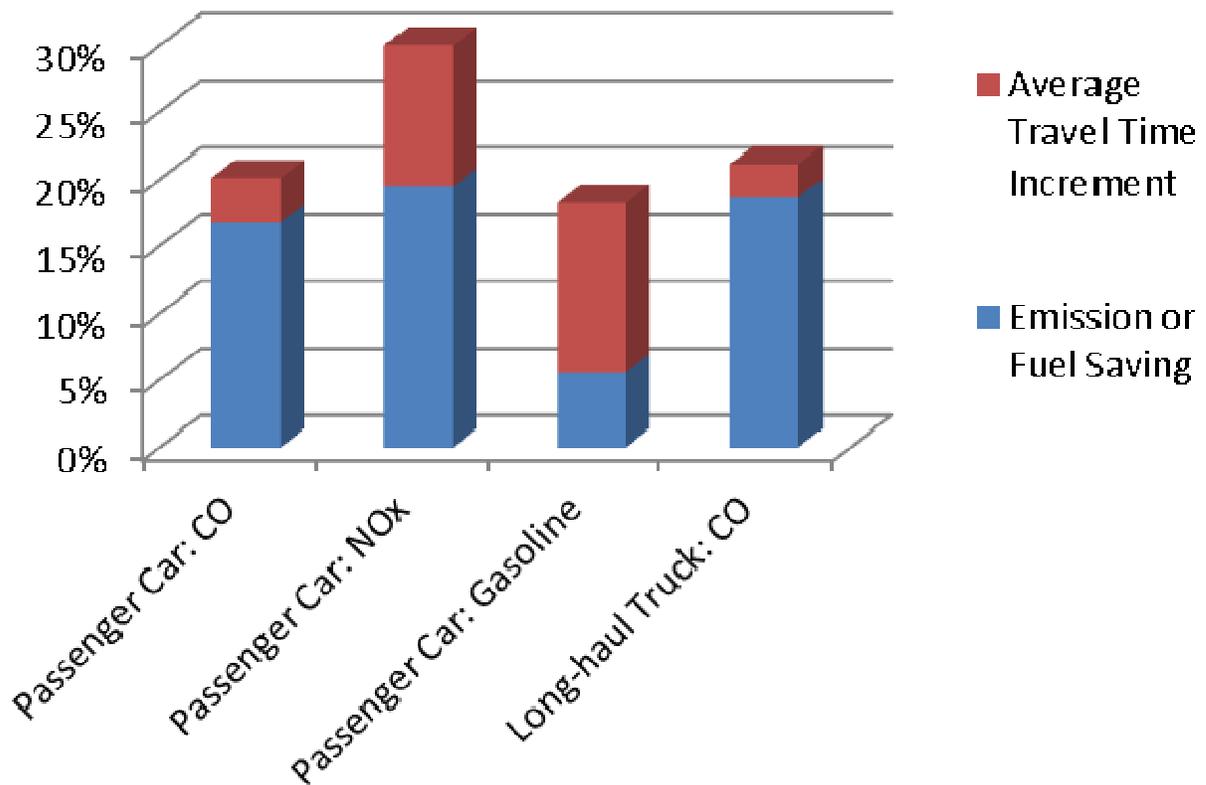
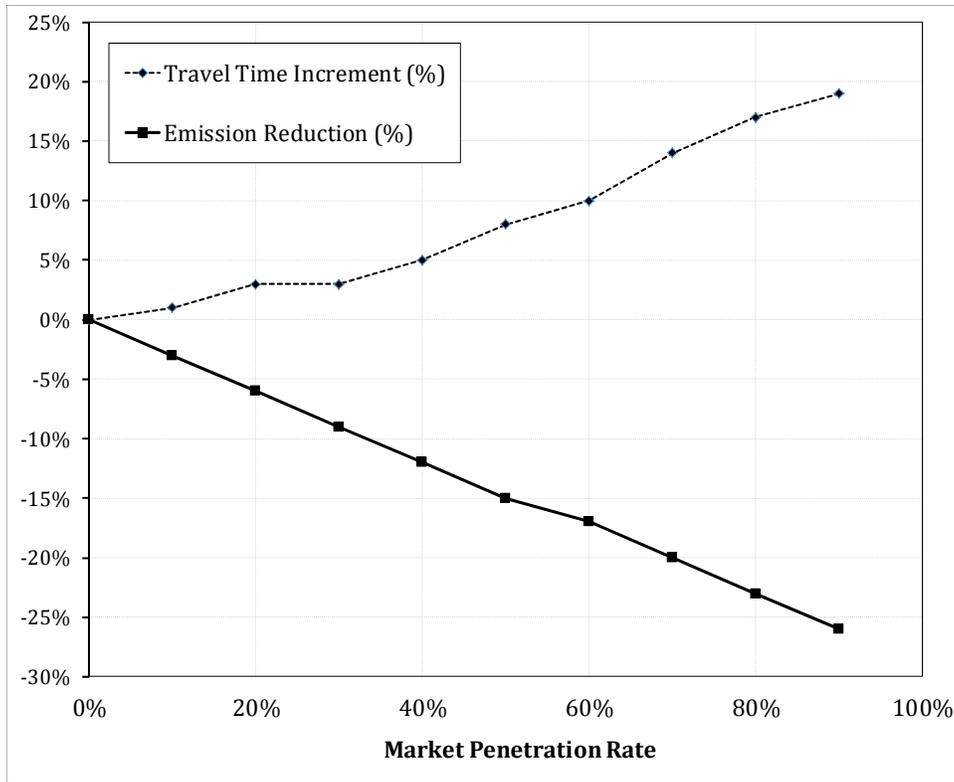


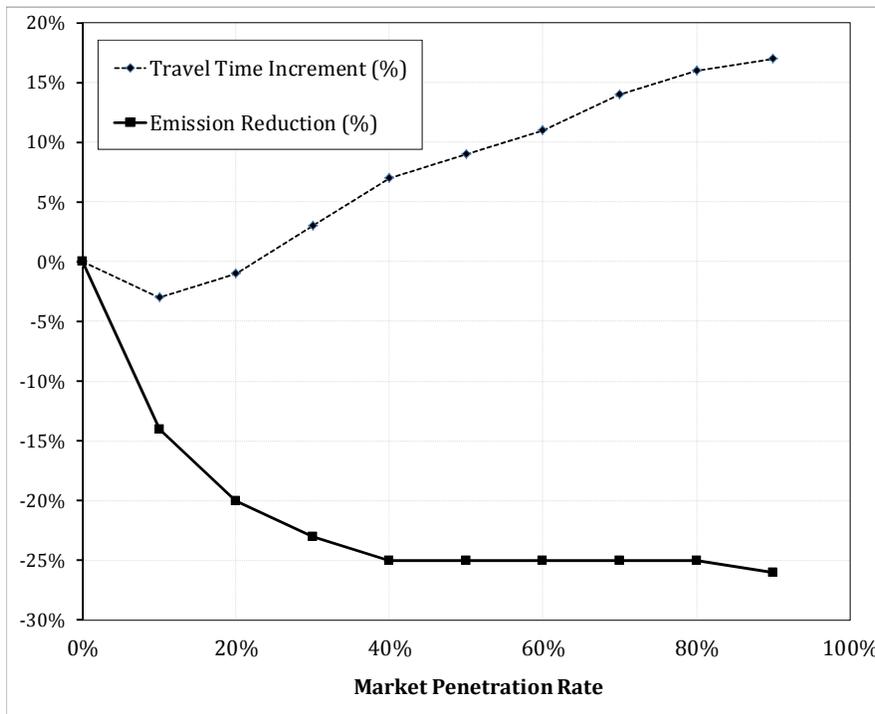
Figure 12. Comparison of the Effects of Green Routing with Different Settings of Pollutants and Vehicle Types

6.2 Market Penetration Results

The results for both random and targeted market penetrations are plotted in Figure 13. Specifically, Figure 13 (a) shows the random market penetration test cases. As can be seen, the system's environmental benefit, i.e., the reduction of emission, is steadily increasing with the increase in the market penetration rate. A corresponding increasing trend in travel time can also be observed from Figure 13 (a), although the rate of increase in travel time appears to be much lower at low penetration rates (i.e., less than 30%) compared to higher penetration rates.



(a) Random Market Penetration



(b) Targeted Market Penetration

Figure 13. Evaluation of Benefits Based on Two Types of Market Penetration Processes

Figure 13 (b) shows the targeted market penetration test cases. Different from the random market penetration tests, the environmental benefit is at first growing dramatically, even at low levels of green routing utilization. However, after reaching 40% market penetration rate, this environmental benefit becomes much less significant with further increases in penetration rates. For the travel time, the overall trend of increment is close to linear except for the 10% case, in which the travel time even decreased (this could be an anomaly caused by the stochastic nature of the system and the fact that UE is only approximated not analytically calculated).

Since the targeted market penetration case better simulates the reality, from the results it can be recommended that the 40% targeted market penetration rate is the optimal. This market penetration rate strikes a good balance between emission reduction and travel time increase for the intelligent green routing users in the future, which are willing to pay reasonable excess travel time to trade for the contribution to the environment.

7 Conclusions and Discussion

In this report, an integration of TRANSIMS and MOVES has been implemented to allow for an iterative feedback procedure for approximating “Green User Equilibrium”. The major contributions that make our report unique are: (1) shedding light on how the MOVES model can be adapted to work with a microscopic traffic simulation model in order to calculate emissions for a realistic regional network rather than just a simple intersections; (2) developing an automated procedure for integrating TRANSIMS and MOVES to allow for microscopic project-level analysis; (3) confirming the conclusions of previous research studies regarding the differences between shortest travel time and least emissions assignments; (4) demonstrating the real potential of green routing strategies to result in significant emissions reductions using a real-world large transportation network; (5) showing that it may be possible to devise green routing strategies that strike a balance between emissions reductions and the expected corresponding increase in travel time; (6) assessing the impact of market penetration rates of green routing users on the system-wide emissions and travel time; and (7) demonstrating the great potential of achieving significant emissions reductions at low market penetration rates if travelers with the largest likely emissions savings are intelligently selected for green routing.

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