A COMPARATIVE EMPIRICAL ANALYSIS OF ECO-FRIENDLY ROUTES
DURING PEAK AND OFF-PEAK HOURS

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Abstract

Automobile emissions reductions can come from several sources that include more efficient vehicles, cleaner fuels, and eco-friendly routing. Providing information about expected emissions on alternative routes can influence route choice of drivers, encouraging some to take more eco-friendly routes. During off peak hours, when substantial capacity is available, the eco-friendly route is likely to be non-changing. However, during peak periods, with limited additional capacity, the eco-friendliness of various routes may change, depending on traffic congestion. To explore this issue empirically, more than 13,330 km of data were collected using GPS equipped-vehicles, in the US and Portugal. Specifically, data were collected in diverse locations: a large metropolitan area of Hampton Roads, VA, USA, intercity region of Oporto–Aveiro, Portugal, and the city of Aveiro, Portugal. The results are based on second-by-second vehicle dynamics, using the Vehicle Specific Power (VSP) concept to extract the emissions on various route alternatives between origins and destinations. During peak hours (and off-peak), a selection of eco-friendly routes can lead to significant savings in global pollutants (up to 25% of CO$_2$) and local pollutants (up to 60% for HC, NO$_X$, and CO). Moreover, these savings were practically unchanged during the peak hours for the two case-studies. In some situations the lower emissions routes are those that cut across urban areas, instead of bypassing them. The implications for future eco-routing systems are discussed.
1. INTRODUCTION AND OBJECTIVES

Transportation is heavily dependent on gasoline and related products for 96% of its energy needs in EU (1). In the European Union, oil dependence of transport could represent about 90% of energy needs by 2020 (1). The inefficient use of transport networks is another major problem. In Europe, traffic congestion costs can increase by 50% by 2050. In the US congestion costs have also increased substantially. In 2009 US spent about $115 billion in expenses related to extra time in traffic and wasted fuel (2).

It is clear that innovative technologies for vehicles are important but traffic management will play a major role in reducing automobile emissions. The integration of traffic management and traveler information systems may influence travel behavior since users of the system can adjust their departure times, destinations or route choices in response to more complete information, including eco-friendliness of alternative routes (3-5).

Route choice decisions can play a substantial role in terms of emissions reduction and energy consumption (6). Currently, widespread information about which routes are more eco-friendly is not widely available. The authors’ earlier efforts were based on generating information about emissions of route alternatives (using a standard vehicle). In non-congested situations there may be sufficient capacity to accommodate the demand of drivers who want to choose an eco-friendly route. However, during peak hours when capacity is limited, eco-friendliness of routes may change (7).

This study explores the impacts of route choice decision during peak hours. The information generated in this study can be useful in implementing innovative and sustainable traffic management strategies. This paper intends to focus on the following questions:

- How can peak hour affect the choice of an eco-friendly route?
- How do tailpipe emissions vary during peak hour on different routes and in different environments?
- How do traffic volumes affect emissions on different network links?

2. LITERATURE REVIEW

The effect of route choice in reducing emissions has been addressed by several authors. Table 1 lists the most relevant studies carried out in the field of route choice optimization, considering energy and air quality. Furthermore, it indicates the methodology for emissions and fuel use estimation (m – microscale models; M–Macro; Me–Meso, f–field measurement) and whether route characteristics (RC) (type of road, incidents, traffic signals, neighborhood, safety) are considered, yes (y) or not (n).

These studies can be divided into two groups. In the first (8-13), the authors developed mathematical formulations to assign traffic on a virtual network considering air quality. In a recent study, mathematical programs integrating emission objective into system wide travel time minimization were developed. It was found that in an idealized system optimum (SO) scenario, CO emissions reduction and travel time minimization can occur when drivers chose longer routes with low speed profiles instead of all users selecting the route with the shortest travel time, i.e., user equilibrium. Another study developed a theoretical emissions-optimized (EO) traffic assignment model. First the authors focused on standard user-equilibrium (UE) and system-optimal (SO) assignment methods, and then they derived two new functions to characterize link emissions and vehicle emissions. It was found that under EO conditions the percentage of traffic assigned to freeways is very low since emissions rates are extremely high at freeway free-flow speeds.

Moreover, the EO assignment is most effective when the network is under low to moderately congested conditions (12). Other authors employed different solutions such as Genetic Algorithms (8) to solve complicated optimization problems with non-linear terms. Overall, reductions in
emissions can be achieved, if travelers choose eco-friendly routes. However, in the extreme case of
everyone choosing an eco-friendly route, a shift to all-or-nothing assignment from UE assignment
may occur.

In the second group (6-7, 14-23) field experiments were conducted and a wide range of
models were applied to evaluate the impact of route selection in terms of emissions and energy use,
over several case-studies. The research of Rakha, Frey and Barth should be highlighted for different
reasons. Ahn and Rakha (19) studied two alternative routes using different type of emission models
which allowed concluding that macroscopic emission estimation tools can yield incorrect
conclusions. In 2011, Rakha et al. also presented a framework for modeling eco-routing strategies
(10). Barth et al. developed and patented an environmentally-friendly navigation system (20, 24)
Frey et al. (7) carried out experiments using a portable emission measurement system (PEMS) under
real world driving cycles. Then, in order to standardize the comparisons of emission rates for
different vehicles and routes, the authors employed the Vehicle Specific Power (VSP) approach to
characterize fuel use and emissions (7). VSP variable can explain a significant portion of variability
in fuel consumption and emissions (25-26).

The majority of studies have concluded that route choice has a significant impact on
emissions and energy use. However, few studies have addressed the effect of congested periods on
emissions (27). The distribution of vehicle speeds and accelerations in traffic vary by type of road
facility and amount of traffic volume, generating large discrepancies in emission levels (28).
Possibly, this fact has contributed to some inconsistency on literature about this issue. On the one
hand, some studies pointed out that time minimization paths often also minimize energy use and
emissions (7, 20, 29). On the other hand, research demonstrated that frequently the faster
alternatives are not the best from an environmental perspective (6, 14, 19, 22).

What has arisen from literature review is that it is not possible to generalize conclusions,
considering the limited study areas, and thus more research is needed to evaluate a wider range of
driving patterns conditions, namely at different periods of the day. A more extensive analysis
including different scales, and different traffic volumes, as performed here, may better reflect the
reality and improve the knowledge to develop further traffic management strategies.
### TABLE 1 Most relevant research on the impact of route choice in terms of emissions and energy consumption

<table>
<thead>
<tr>
<th>Reference</th>
<th>Study Location</th>
<th>Environmental Goals</th>
<th>Emissions Estimation</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nagurney et al. (1998)</td>
<td>Virtual</td>
<td>Generic</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Sugawara and Niemeier (2002)</td>
<td>Virtual</td>
<td>CO</td>
<td>M (f(average speed))</td>
<td>NA</td>
</tr>
<tr>
<td>Figliozzi (2010)</td>
<td>Virtual</td>
<td>CO₂</td>
<td>M (f(average speed))</td>
<td>NA</td>
</tr>
<tr>
<td>Rakha et al. (2011)</td>
<td>Virtual</td>
<td>Fuel, CO₂</td>
<td>m (VT-micro)</td>
<td>NA</td>
</tr>
<tr>
<td>Abdul Aziz and Satish Ukkusuri (2011)</td>
<td>Virtual</td>
<td>CO</td>
<td>M (f(average speed))</td>
<td>NA</td>
</tr>
<tr>
<td>Ferguson et al. (2011)</td>
<td>Virtual</td>
<td>VOC, NOₓ CO</td>
<td>M (f(average speed))</td>
<td>NA</td>
</tr>
<tr>
<td>Gwo-Hshing Tzeng and Chien-Ho (1993)</td>
<td>Taipei, Taiwan</td>
<td>CO</td>
<td>M (Local survey)</td>
<td>n</td>
</tr>
<tr>
<td>Rilett and Benedek (1994)</td>
<td>Ottawa, Canada</td>
<td>CO</td>
<td>M (f(average speed))</td>
<td>n</td>
</tr>
<tr>
<td>Ericsson et al. (2006)</td>
<td>Lund, Sweden</td>
<td>Fuel, CO₂</td>
<td>m (VETESS, VETO)</td>
<td>y</td>
</tr>
<tr>
<td>Barth et al. (2007)</td>
<td>Los Angeles CA, US</td>
<td>CO, CO₂, NOₓ, HC, FUEL</td>
<td>m (CMEM)</td>
<td>n</td>
</tr>
<tr>
<td>Frey et al. (2008)</td>
<td>North Carolina, US</td>
<td>HC, NOₓ, CO₂, CO, FUEL</td>
<td>PEMS &amp; m (VSP)</td>
<td>n</td>
</tr>
<tr>
<td>Ahn and Rakha (2008)</td>
<td>Northern Virginia, US</td>
<td>NOₓ, CO₂, FUEL, HC, CO</td>
<td>M&amp;m (VT-micro, CMEM, Mobile6)</td>
<td>n</td>
</tr>
<tr>
<td>Feng et al. (2008)</td>
<td>Dalian, China</td>
<td>CO</td>
<td>M (f(average speed))</td>
<td>n</td>
</tr>
<tr>
<td>Tavares et al. (2009)</td>
<td>Cape Verde</td>
<td>Fuel, CO₂</td>
<td>M (Copert)</td>
<td>y</td>
</tr>
<tr>
<td>Zhang and Ying (2010)</td>
<td>Virtual and College Station, TX, US</td>
<td>CO</td>
<td>M (Mobile 6,2)</td>
<td>n</td>
</tr>
<tr>
<td>Ganti et al. (2010)</td>
<td>Urbana-Champaign, US</td>
<td>Fuel</td>
<td>Me (f(Speed, traffic lights, slope, car))</td>
<td>n</td>
</tr>
<tr>
<td>Bandeira et al. (2011)</td>
<td>Aveiro-Porto, Portugal</td>
<td>NOₓ, CO₂, HC, CO, FUEL</td>
<td>m (VSP)</td>
<td>y</td>
</tr>
<tr>
<td>Minett et al. (2011)</td>
<td>Zoetermeer, Holland</td>
<td>Fuel</td>
<td>m (VT-CPFEM)</td>
<td>n</td>
</tr>
</tbody>
</table>

(m – micro or M – Macro; - Route characteristics (type of road, incidents, traffic signals, neighborhood, etc.) are considered (y) or not (n).
3. METHODOLOGY

3.1 Experimental Measurements

Data for approximately 13,300 km of road coverage over the course of 222 hours were collected, in different traffic conditions both in the USA and Portugal: a metropolitan area (Hampton Roads, VA, USA) an intercity region (Oporto–Aveiro, Portugal) and a medium-sized city (Aveiro, Portugal). For all origin/destination pairs the study routes were based on suggestions from an internet trip-planning software (Google-maps). The study maps and route characteristics are shown in Figure 1 and Table 2. Regarding urban routes, all paths connect the city centre to a point located in the suburbs. Route RA is predominantly (56%) driven on motorway A25, Route RB essentially uses the arterial road N109. Finally, Route RC is entirely contained in a compact urban environment. In each direction significant length differences are observed due to traffic constrains. Concerning intercity routes, four parallel alternative routes that cross some of the most densely populated areas of Portugal were considered. While R1 and R2 are based on the motorways A1 and A29, respectively (with a toll cost of 5 Euros), R3 and R4 are mainly performed on national roads. Both for intercity and urban routes, off-peak emissions and a detailed route characterization can be found elsewhere (6).

In this paper a new pair origin-destination was considered. Thus, two alternative routes with similar travel times were examined both at peak and off-peak hours. Both routes connect the Old Dominion University in Norfolk, to a large commercial area in Chesapeake. Those routes have high quality data on traffic volumes and, road characteristics. RD is mostly performed on an arterial roads (60% of 21.4 km (13.3 mi)), crossing downtown Norfolk. Regarding RE, 70% of the route distance (29.2 km (18.3 mi)) is traveled through the I-64, bypassing the city of Norfolk to the East. Although RE presents more intersections, the majority of them are uncontrolled connections to residential neighborhoods with little impact on the arterial roads.

The road tests were performed during weekdays under dry weather conditions during the months of February, March and April of 2010 and 2011. According to traffic volume data (30-31), the peak period in the US site was considered between 6-8 AM and 4-6 PM while in Portugal (PT) the peak period was considered between 7-9 AM and 5-7 PM. So, all trips whose departure time was within this time range are defined as peak hour tests. The off-peak tests occurred between 9 AM-4 PM (US) and 10 AM-5 PM (PT). The US tests were performed using the same driver and vehicle (Nissan Versa 1.6 L), while in the Portuguese case-studies, three different drivers and vehicles (Toyota Prius 1.8; VW Polo 1.2; and Opel Corsa 1.2) were used. All drivers tried to avoid hard accelerations and keep the average speed of the traffic flow. When the traffic volume was low, the speed limits were respected. Although some slight differences on emissions according to the driver were verified, the route choice was shown to be the main factor that control emissions (6).

During experimental tests, vehicles dynamics were recorded second-by-second, using GPS data-logger devices with a resolution of 5 Hz. Videotaping was also performed to record route characteristics and other incidents that may affect emissions.
TABLE 2 Characteristics of the corridors

<table>
<thead>
<tr>
<th>Route</th>
<th>Length (km)</th>
<th>Speed limits (% of distance)</th>
<th>Number of Lanes (% of distance)</th>
<th>Intersections</th>
<th>Ramps</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA-CS</td>
<td>6.9</td>
<td>50 (29%), 70 (13%), 120 (58%)</td>
<td>2 (29%), 4 (71%)</td>
<td>11</td>
<td>TL 1</td>
</tr>
<tr>
<td>RA-SC</td>
<td>5.8</td>
<td>50 (32%), 70 (2%), 120 (66%)</td>
<td>2 (32%), 4 (68%)</td>
<td>10</td>
<td>R 1</td>
</tr>
<tr>
<td>RB-CS</td>
<td>6.4</td>
<td>50 (66%), 70 (34%)</td>
<td>2 (45%), 4 (55%)</td>
<td>10</td>
<td>On 5</td>
</tr>
<tr>
<td>RB-SC</td>
<td>5.7</td>
<td>50 (63%), 70 (37%)</td>
<td>2 (39%), 4 (61%)</td>
<td>8</td>
<td>Off 15</td>
</tr>
<tr>
<td>RC-CS</td>
<td>4.3</td>
<td>50 (100%)</td>
<td>4 (60%), 2 (40%)</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>RC-SC</td>
<td>4.1</td>
<td>50 (100%)</td>
<td>4 (60%), 2 (40%)</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

**Urban**

<table>
<thead>
<tr>
<th>Route</th>
<th>Length (km)</th>
<th>Speed limits (% of distance)</th>
<th>Number of Lanes (% of distance)</th>
<th>Intersections</th>
<th>Ramps</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA-CS</td>
<td>6.9</td>
<td>50 (29%), 70 (13%), 120 (58%)</td>
<td>2 (29%), 4 (71%)</td>
<td>11</td>
<td>TL 1</td>
</tr>
<tr>
<td>RA-SC</td>
<td>5.8</td>
<td>50 (32%), 70 (2%), 120 (66%)</td>
<td>2 (32%), 4 (68%)</td>
<td>10</td>
<td>R 1</td>
</tr>
<tr>
<td>RB-CS</td>
<td>6.4</td>
<td>50 (66%), 70 (34%)</td>
<td>2 (45%), 4 (55%)</td>
<td>10</td>
<td>On 5</td>
</tr>
<tr>
<td>RB-SC</td>
<td>5.7</td>
<td>50 (63%), 70 (37%)</td>
<td>2 (39%), 4 (61%)</td>
<td>8</td>
<td>Off 15</td>
</tr>
<tr>
<td>RC-CS</td>
<td>4.3</td>
<td>50 (100%)</td>
<td>4 (60%), 2 (40%)</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>RC-SC</td>
<td>4.1</td>
<td>50 (100%)</td>
<td>4 (60%), 2 (40%)</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

**Intercity**

<table>
<thead>
<tr>
<th>Route</th>
<th>Length (km)</th>
<th>Speed limits (% of distance)</th>
<th>Number of Lanes (% of distance)</th>
<th>Intersections</th>
<th>Ramps</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>77.1</td>
<td>50 (2%), 90 (7%), 120 (91%)</td>
<td>2 (2%), 4 (82%), 6 (1%), 8 (8%)</td>
<td>9</td>
<td>3 26</td>
</tr>
<tr>
<td>R2</td>
<td>77.0</td>
<td>50 (2%), 90 (7%), 100-120 (91%)</td>
<td>2 (2%), 4 (87%), 6 (11%)</td>
<td>9</td>
<td>1 35</td>
</tr>
<tr>
<td>R3</td>
<td>87.2</td>
<td>50 (2%), 50/70 (58%), 90 (7%), 120 (48%)</td>
<td>3 (12%), 4 (33%), 6 (7%)</td>
<td>135</td>
<td>20 7</td>
</tr>
<tr>
<td>R4</td>
<td>75.7</td>
<td>50 (23%), 50/70, (68%), 90 (6%), 122 (88%); 4 (2%), 6 (10%)</td>
<td>2 (5%), 4 (31%), 6 (59%), 8 (5%)</td>
<td>275</td>
<td>17 0</td>
</tr>
</tbody>
</table>

**Metropolitan**

<table>
<thead>
<tr>
<th>Route</th>
<th>Length (km)</th>
<th>Speed limits (% of distance)</th>
<th>Number of Lanes (% of distance)</th>
<th>Intersections</th>
<th>Ramps</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD</td>
<td>21.4</td>
<td>48 (32%), 64 (15%, 80 (34%), 96 (12%))</td>
<td>4 (13%), 6 (47%), 8 (37%)</td>
<td>55</td>
<td>12 13</td>
</tr>
<tr>
<td>RE</td>
<td>29.2</td>
<td>48 (20%), 64 (10%), 96 (70%)</td>
<td>2 (5%), 4 (31%), 6 (59%), 8 (5%)</td>
<td>47</td>
<td>17 17</td>
</tr>
</tbody>
</table>

TL – Traffic lights, R - roundabouts

FIGURE 1 Study routes map - a) Intercity: R1, R2, R3 and R4, b) Metropolitan: RD and RE with VDOT segments, c) Urban RA, RB and RC.
3.2 Emissions estimation

For consistency with the previous study, the same methodology based on VSP categorized in 14 modes was used to estimate pollutants emissions (global CO$_2$, and local CO, NO$_X$ and HC) from Light Diesel Duty Vehicles (LDDV) and Light Gasoline Duty Vehicles (LDGV). Summing up, the calculation of the VSP variable follows the equation (1) but a more detailed explanation on the methodology used can be found elsewhere (6, 25-26).

\[
VSP = v[a + 9.81 \sin(\arctan(\text{grade})) + 0.132] + 0.000302 \times v^3 (1)
\]

where:

- VSP = Vehicle Specific Power (kW.ton$^{-1}$)
- v = speed (m/s)
- a = acceleration (m/s$^2$)
- Grade = road grade (decimal fraction)

The LDDV (<3.5 L) and LDGV (<1.8 L) emissions rates used in this research can be found in the references (25-26). Total pollutants emissions by route were derived based on the average time spent in each VSP mode multiplied by its respective emission factor. Besides VSP explains a substantial portion of variability in tailpipe emissions (26), VSP was also shown to be appropriate for the purpose of relative comparisons between alternative routes (7).

4. DISCUSSION AND RESULTS

4.1 Analysis of VSP modal frequency

Since it is the frequency of occurrences of each VSP mode that control the total of emissions estimated, it is important to understand how VSP modes distribution varies across routes. A comprehensive analysis of the time spent in each driving VSP mode was carried out.

Modes 1 and 2 represent deceleration modes, whereas mode 3 represents idling situation. Modes 4 to 14 describe combinations of increasing and positive accelerations. The columns charts shown in Figure 2 display the average time spent in each VSP mode during off-peak and peak periods, with the respective standard deviation. The solid lines represent the relative frequency distribution of the VSP modes, whereas the round dot and the long dash lines indicate the relative contribution of each VSP mode for the total of CO$_2$ and CO emissions, respectively.

For each OD pair, key route attributes were considered. R1 and R4 have a similar length but during peak and off-peak R1 allows more than 50% of time saving in relation to R4. RD and RE have comparable travel times but RD is 27% shorter. Regarding the urban routes, RA is the longest but with less travel time. Thus, the routes R1, RE and RA (the faster routes performed essentially on motorways) have a more uniform VSP modes distribution compared with Routes R4, RD and RC predominantly driven on urbanized areas, where the reduction of speed shift the distribution towards lower VSP modes. For instance, on R4 14% (off-peak) and 20% (peak) of the time is consumed in idling situations and just 4% of the travel time is spent on VSP modes higher than 7. Standard deviations intervals showed a higher variability in Routes R4, RD, and RC, particularly in VSP mode 3, due to the natural variability, such as traffic lights, illegal parking, and congestion, which increases idling.
The distribution of CO$_2$ according to the VSP mode follows approximately the same trend of the relative frequency distribution of VSP modes. However, CO emissions are mostly generated during the occurrence of the higher VSP modes. For instance on RD, more than 40% of CO emissions are generated during the occurrence of the VSP modes 12, 13 and 14 which represent nearly 2% of the travel time. The contribution of each VSP mode for the remaining local pollutants is not shown. However, a detailed analysis of these pollutants (NO$_X$ - LDDV, and HC - LDGV) showed comparable behavior to CO emissions, but less sensitivity to the higher VSP modes (11-14).

FIGURE 2 VSP mode frequencies (with standard deviation intervals); VSP modes relative frequency distribution at peak and off-peak; and contribution of each VSP mode for CO$_2$ and CO emissions at peak period: Intercity routes (R1, R4); Regional routes (RD, RE); Urban routes (RA, RC).
4.2 Total emissions per route

Table 3 provides descriptive statistics for all study routes. The data are broken down by study-area, route, time period and the difference occurred between peak and off-peak. Once the results are relatively similar in both directions only one direction is presented. The number of samples performed for each situation (N), average speed, and total emissions focusing on CO₂, CO, and HC from LDGVs, and NOₓ from LDDVs (the major sources of each pollutant) are presented. For each OD pair the best route for all parameters is underlined. The column “reduction” shows the potential reductions in emissions by comparing each route with the worst. To address possible trade-offs between travel time (T.T) and emissions minimization, the relative increase in travel time compared with the fastest route is presented in the last column of the table.

Table 3 Descriptive statistics of Average speed, Travel Time NOₓ emissions, from LDDV and CO₂ / CO emissions from LDGV (intercity– Aveiro-Oporto; regional – Norfolk-Chesapeake; urban – Centre-Suburbs)

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Av Speed (km/h)</th>
<th>Travel Time (min)</th>
<th>D NOₓ (g)</th>
<th>G CO₂ (g)</th>
<th>G CO (g)</th>
<th>Reduction</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>P95</td>
<td>Mean</td>
<td>P95</td>
<td>Mean</td>
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<td></td>
<td></td>
<td>Mean</td>
<td>P95</td>
<td>Mean</td>
<td>P95</td>
<td>Mean</td>
<td>P95</td>
<td>Mean</td>
</tr>
<tr>
<td>off-peak</td>
<td>6</td>
<td>95</td>
<td>99</td>
<td>50</td>
<td>51</td>
<td>71</td>
<td>81</td>
<td>119</td>
</tr>
<tr>
<td>R1 peak</td>
<td>13</td>
<td>93</td>
<td>97</td>
<td>50</td>
<td>52</td>
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Figure 3 shows the evolution of a local pollutant (CO) and a global pollutant (CO₂) as function of average speed, being also observable the peak impact on emissions and average speed.
Concerning intercity routes, the motorway options (R1 and R2) are less time consuming than the alternative routes R3 and R4 during off-peak. During peak periods these differences are increased to 99% and 104% respectively. In this situation it seems that the network is not going toward the user equilibrium. The fact is that R1 and R2 have toll costs, while R3 and R4 have a lower capacity compared to the freeway routes. The increase of (local and regional) traffic volume during peak periods seems to result in a higher travel time differences. The 95th percentile values, as well as the distribution of data points along average speed axis (Figure 3) suggest that Routes R2, R3 and R4 at peak hours have lower reliability.

CO₂ emissions data show that motorway routes (R1 and R2) lead to less fuel consumption while R4 shows the opposite trend. This can be confirmed in Figure 3 in which a general trend of decreasing CO₂ emissions with average speed is clear. However, according to the literature (32-33) for average speeds values beyond the experimental range (>100 km/h (62 mph)), CO₂ emissions would tend to increase again. It can be also observed that during the peak period, CO₂ total emissions show a higher increase on the national roads (R3, R4), due to more congestion and higher travel times. Concerning local pollutants the effect of peak demand is more obvious on the freeway routes R1 and R2. For R3 and R4 the local pollutants emissions do not change significantly during the peak periods.
period. Although the travel time is higher the decrease of the frequency of the upper VSP modes has contributed to emission reductions. Finally, there is an evident trade-off between CO$_2$ and local pollutants minimization, confirming the findings in (6).

Regarding regional routes, RE has the highest emissions. Both at peak and off-peak, RD yielded CO$_2$ emissions saving from 7% up to 14% and CO savings of up to 14%. RE was found to be a better option only in the case of CO emissions during peak period and in the direction Norfolk-Chesapeake. A more detailed analysis showed that on RD, the CO emissions are mostly produced during the 6 km freeway section included in this route.

Evaluating the average emission rates per distance (km), CO$_2$ and CO emissions rates on RD were found to be 1.27 and 1.18 times higher than RE. However, RE is 1.3 times longer than RD which makes RD more environmentally friendly in terms of total emissions produced. CO$_2$ emissions follow the same trend observed in intercity routes i.e., total emissions decrease inversely to average speed. A higher variability for all pollutants emissions values is observed in RD as can be confirmed by the higher standard deviation and dispersion of data emissions points in Figure 3. This can be explained by the fact that a significant distance of RD is traveled through downtown Norfolk, being mostly performed on arterial roads and covering more signalized intersections, which lead to a certain unpredictability in the speed profile.

Regarding travel time, in the Norfolk-Chesapeake direction, RE is likely to be the favorite choice for many drivers, offering an average time reduction of about 10% over RD during off-peak periods. During peak hours RD and RE have similar travel times.

Finally, concerning urban routes, the peak demand effect is more evident on RC (centre-suburbs), although it is still the best route considering the minimization of pollutants emissions. Once more, this route yields the highest emissions rate per distance but its shorter length leads to a reduction in total emissions. On RA a high variability in CO emissions was noticed which can be to a certain extent explained by different driving behaviors (6).

Overall, regarding CO$_2$ emissions (and fuel consumption), a higher correlation between an increase in average speed (inter-trip, the same route) and the reduction of CO$_2$ emissions rates is evident. However, total emissions can be reduced if a considerably shorter path is found, as in the case of RC and RD. With respect to local pollutants, although there is a higher variability in comparison to CO$_2$ emissions, it is evident a general trend to emissions increase with speed.

Across US and European routes, the most eco-friendly route during off-peak is also eco-friendly during the peak hour. These results suggest that for a limited percentage of drivers diverting to these eco-routes, no significant impacts will be observed on the network. However, for future implementations of eco-routing strategies in different areas it will be important to evaluate the capacity of each segment and their ability to accommodate additional demand.

### 4.3 Link-Based Emissions

Link-based emissions were estimated for peak and off-peak hours, using the second-by-second field data for all VDOT road segments on regional routes (Figure 4). In the majority of the sections, CO$_2$ emissions during peak are consistently higher than during off-peak. E-D and D-K are the segments where the highest increase at peak hour is experienced. This can be explained by the frequent traffic jams that occur at peak hours since these links serve as connector to the belt roads I-64 and I-264/I-464, respectively. In I-464 segments (DL-DQ), there are no significant differences between peak and off-peak, because even at peak a high volume/capacity ratio is maintained. On the other hand the I-64 segments (E-D to E-O) are more vulnerable to higher traffic volumes, particularly on the northern sections E-G and E-I. A slight decrease (but not significant) in emissions at peak period is observed on E-A, D-A, D-B, D-C.
One method to estimate the energy and emission effects of congestion is to analyze speed patterns of vehicles operating under different levels of congestion. In this section the way emissions change with traffic volume on certain links of the region is discussed. Using detailed 2009 traffic volumes of 4 winter weekdays and 15-minute raw data, the average speed and total emissions estimated for each link (per lane) was matched with the corresponding traffic volume reported for the respective 15 minutes period. Therefore, it is assumed that traffic volumes variation during experimental tests were similar to 2009. This is an important limitation since vehicle dynamics and traffic volume should be measured simultaneously (using loop sensors, for example). However, the margin of error may be minimal, given that the traffic historical data do not show significant variations of volumes over the last years, and no significant changes in the road network were made. Figure 5 shows CO$_2$ and NOx emissions under different traffic volumes on an arterial and a freeway segments. A rough calculation of the existing capacity in each lane was done. It was estimated that in each freeway lane, there is a capacity of 1700 vehicles per hour (vph) and in each arterial lane 850 vph (assuming an average g/c ratio for through traffic of 0.50).
FIGURE 5  NO\textsubscript{X} and CO\textsubscript{2} emissions as function of traffic volume for an arterial route (E-D) and a freeway segment (E-I).

E-D is a 4-lane arterial segment 500 m long covering 3 signalized intersections, one of which is at the interchange with I-64. Figure 4 shows that this is the road segment of RE where a higher difference in CO\textsubscript{2} emissions between peak and off-peak is observed. E-I segment corresponds to a 3-lane, I-64 section which extends over 2000 meters. According VDOT data, during the peak both segments have been classified as operating in LOS E.

For E-D segment, emissions and average speed remain relatively constant up to a certain traffic volume level. From that point emissions start to increase. A third-order polynomial was used to fit the data points, shown as solid lines in Figure 5. Although more data points are needed to define a statistically valid trend, these results are consistent with previous research (12). A detailed analysis of speed profiles have demonstrated that on E-D segment the emissions are strongly dependent of congestion, namely the coordination between the traffic flow with the timing of traffic lights.

On the freeway segments, relatively high correlations between CO\textsubscript{2}, and traffic volumes were found and the same trend is observed. Thus, for traffic volume higher than the capacity estimated, CO\textsubscript{2} emissions start to increase. However, for local pollutants no correlations were found. It should be noted that although the average speed remains relatively constant in free flow situations, NO\textsubscript{X}, CO and HC show a higher variability, because slight speed variations produce a significant impact on local pollutants.

Real time or historical link based-emissions can be incorporated in pre-trip planning software to determine the most eco-friendly route. In the context of dynamic traffic assignment and where real-time information on traffic conditions and emissions is available, new routing algorithms can be developed based on the UE perspective. However, when there is no real-time information, pre-trip
planning programs can consider the variability of emissions on each link based on different time periods and estimate the best route for a specific period. This is valid assuming that the impact of these programs will not have a substantial impact that dramatically changes the equilibrium in the network.

4. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

This paper has attempted to assess whether eco-friendly routes change during peak hours, based on three distinct case-studies on two continents. A total of 222 hours of GPS data were collected and a microscale vehicle-based approach was used to generate emissions information during peak and off-peak periods.

Although these field tests have been conducted in regions with very different characteristics, the results cannot be generalized to other locations. However, this study has confirmed the potential of the eco-routing concept and has also identified some limitations that must be considered when implementing these systems.

In general, it was demonstrated empirically that for the situations examined, the route that is the most eco-friendly during off-peak is also the most eco-friendly during the peak hours. These results suggest that for limited market penetration of eco-friendly navigation systems (using link based emissions data) there can be sufficient capacity to accommodate demand without increasing emissions in the network. In a more advanced ITS scenario, in which vehicles are routed dynamically in the network, the changes in traffic volumes between the various routes can be significantly higher. In this scenario, one must consider each road segment capacity to accommodate more traffic without increasing emissions.

Regarding intercity routes both tests conducted during the peak and off-peak hours have shown the faster routes can reduce both CO$_2$ emissions and fuel consumption up to 30%. However, if the main objective is to minimize local pollutants emissions, this case-study has shown that travel time may significantly increase by vehicles taking national roads. On regional and urban routes, the shortest path was shown to be the best option to reduce the emissions.

For all case-studies, the routes that lead to a minimization of local pollutants are those that mainly cross urbanized areas, avoiding motorways. This fact will involve a careful assessment of potential externalities that may arise from a purely dedicated navigation system based on emissions minimization, since higher volumes of traffic crossing urban areas may lead to urban environmental degradation and worse levels of road safety.

Thus, in addition to the environmental information that can be provided to the drivers, some alternative traffic management strategies may be implemented to improve traffic operations. For instance implementing speed management/harmonization techniques on freeways aiming at the reduction of excessively high speeds and consequent high emissions levels can be helpful. It can also facilitate the minimization of the trade-off between the minimization of fuel/CO$_2$ emissions and other pollutants, and make less attractive (from the total emissions perspective) the routes that cross the urban centers. Simultaneously several traveler information systems, such as variable message signals, or dynamic road pricing schemes, can persuade drivers to avoid the most congested routes or ones with higher emissions levels.

Further research will focus on the development of an integrated platform which should be able to simulate various ITS scenarios mentioned above, different methods of traffic assignments, and considering the total emissions on the network and externalities (such as road safety) associated with each scenario. Moreover, further research should assess the tradeoff between air quality and human exposure to pollutants, i.e., the issue of diverting traffic to more eco-friendly local streets but the emissions having greater health impacts in densely populated areas.
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REFERENCES


