GENERATING EMISSIONS INFORMATION FOR ROUTE SELECTION – EXPERIMENTAL MONITORING AND ROUTES CHARACTERIZATION

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Abstract

Route selection decisions of drivers are important in how the transportation system performs. While travelers’ route choice decisions are influenced by several factors including travel time and trip distance, it is not clear what impacts, if any, will additional information about emissions have on route choices. This study explores ways to generate information about emissions for people faced with a choice of routes and provides details of the methodology. In this regard, GPS equipped-vehicles were used to traverse various paths between origins and destinations in order to collect second-by-second trajectory data required for microscopic analysis. Then, a methodology based on the Vehicle Specific Power (VSP) concept was used to extract the emissions impact. A video camera was used to record route features, traffic incidents, and congestion levels. Two different vehicles and drivers traversed urban and intercity routes in order to consider the influence of driver behavior and vehicle dynamics. It was found that both at the urban and intercity scales, a combination of an appropriate route and smoother driving styles can result in significant savings of fuel consumption and substantial emissions reductions. Moreover, a trade-off between the minimization of CO2/fuel consumption and the local pollutants was found.

Keywords: Route-choice; Emissions; Vehicle Specific Power (VSP); Driving behavior
1. INTRODUCTION AND OBJECTIVES

Although it is clear that improvements in the technology of vehicles are a key factor in pollution control, changes in citizen’s behavior are also essential. Recognizing that while modal shifts (to transit, bicycle or walking) are legitimate alternative ways to reduce emissions, considerable advances could be also achieved involving targeting route choice for passenger vehicles which constitutes the largest portion of urban travel. Currently, travelers select routes based on several considerations, but a key aspect of their route choice is to minimize travel times. This time minimization is also reflected in the traffic assignment procedures, e.g., user equilibrium assignment, that are widely used in travel demand forecasting. The basic idea of this research is to broaden the route evaluation criteria to include air quality considerations in route choice. That is, at least under uncongested conditions, there may be routes that are longer but better in terms of emissions. However, currently travelers do not have access to information about which routes between an origin-destination pair may result in less or more emissions. This research examines how emissions vary across routes and generates information that can empower travelers who want to use emissions as additional criteria for their route selection. The emissions considered include CO, CO$_2$, HC, and NO$_x$.

2. LITERATURE REVIEW

Route choice behavior has been studied in some depth in recent years. Some studies have focused only on driver preferences (1), and others also have considered the impact of new advanced traffic information systems (2-5). Usually, people prefer to minimize travel time (1) but also may consider distance, avoiding traffic signals, scenery, safety, security or land use surrounding the routes. There is little research regarding the environmental component, but recent works have suggested that it is not unreasonable to presume that some sectors of travellers will consider an environmental criterion into their decision-making process with the increasing concern of the degradation of the environment (6-8).

In the last decades, several researchers have investigated the impact of route choice and traffic assignment in terms of emissions and energy consumption. The first advances in this area were achieved using macroscopic models or average emissions factors per link in conjunction with environmental cost functions (9-11). More recently, a heuristic approach was proposed to reduce the level of emissions given a number of possible routes for commercial vehicles (12). Another study used a genetic algorithm and a cell-based approach to model emission concentrations and assigning traffic in a network taking into account air quality (13).

Some research has been performed equipping vehicles with a portable emission measurement system (PEMS) to analyze emissions under real world driving cycles (14-16). Alternatively, other studies have used GPS equipped vehicles in order to record detailed travel data and carry out the analysis of emissions impacts and energy consumption. The use of GPS equipped vehicles has proved to be a good method to measure a real-world operating mode for emissions research (17). Based on GPS data, Ahn and Rakha (18) have studied emission rates for different vehicle types and routes using microscopic and macroscopic emission estimation tools; however, an extensive characterization of the routes was not performed. The use of geographic information systems and network analysis also has demonstrated to be an important mechanism to develop routing algorithms in order to minimize fuel consumption and emissions.
considering emission factors according to specific link characteristics (19). In the same
context, Barth et al. (20) developed an environmentally-friendly navigation system
consisting of a link-based energy and emission factors indexed by link characteristics
such as flow, density, speed, and grade.

The main conclusions of previous research are that there is a trade-off between
reductions in travel time and improvements of air quality (13), and emission-optimized
trip assignments can reduce system-level vehicle emissions reasonably when compared
to the time-dependent user equilibrium and system optimum conditions (21). It was also
demonstrated that an average of 8.2% fuel could be saved using a fuel-optimized
navigation system (19). Regarding emissions modelling, it could often be risky to
oversimplify the results of macroscopic traffic assignment models to actual traffic
systems (18).

What has arisen from the literature review is that a deeper understanding of the
influence of the roads characteristics and driver behavior in emissions rates is lacking.
Moreover the authors could not find any study considering alternative routes in urban
and inter-city contexts. In areas where there is no real-time traffic data on traffic
performance the knowledge of road characteristics and their influence on emissions
behavior could be an important instrument. Many of the devices allowing friendly
navigation routing that have emerged are based on fuel saving and lower CO₂
emissions. It is certainly true that this is a very important improvement regarding global
warming. However, these systems do not consider local pollutants which have direct
impact on human health. It is still necessary to improve the knowledge about the role
that driver behavior or vehicle dynamics could play in choosing an environmentally
friendly route (e.g. a route with a lower level of emissions).

Thus, the main goals of this research were to:

1) Evaluate study corridor characteristics in terms of travel time, average speed,
and reliability at urban and inter urban scales;
2) Develop a methodology based on micro-scale simulation in order to analyse the
impact of route choice and its characteristics in terms of vehicle dynamics and
emissions;
3) Assess the importance of driver behaviour and vehicle type on emissions;
4) Generate information that may be available to drivers through Advanced
Transportation Information Systems (ATIS).

3. METHODOLOGY

3.1 Experimental Measurements – Vehicle Dynamics

To identify the energy and emissions impacts of route choice behavior, GPS data were
collected both in the city of Aveiro and between the cities of Aveiro and Oporto, in
Portugal. The field experiments were performed specifically in off-peak periods (10:30
AM - 1:00 PM and 2:30 PM – 5:00 PM), in order to analyze the inherent characteristics
(grade, intersections density, speed profiles) of the routes without the influence of
significant changes in traffic. The road tests were performed during week days under
dry weather conditions between March and April 2010. Three distinct data sets were
gathered for all routes: DAV1 (Driver A – Vehicle 1); DBV1 (Driver B – Vehicle 1);
and DAV2 (Driver A – Vehicle 2). Both drivers tried to keep the average speed of the
traffic flow.
The GPS equipment presents two important features: 1) registration of second-by-second vehicle location and speed; and 2) the ability to transfer data collected to a computer via USB. The equipment has an active, high sensitivity antenna with an accuracy of 1 to 5 m and a 1 Hz update rate. Velocity and acceleration data were gathered directly from the GPS data logger. Altitude and Elevation change data were obtained through a Digital Elevation Model based on geographic position using the database NASA - SRTM 90m available from an online source (22). Generally, the signal losses were not significant to the extent that it affects the overall results. Even in urban areas GPS signal was not affected considerably, since the studied region consists of buildings with fewer floors which does not affect GPS signal quality.

Simultaneously, routes videotaping was performed, with the purpose of characterizing them in various aspects (e.g. number and type of intersections, pavement preservation, number of lanes), and specific traffic situations or incidents that can influence emissions and fuel consumption (e.g. pedestrians density, illegal parking, road works).

To analyse the impacts of route choice behavior on an urban scale, three alternative routes (RA, RB, RC) in Aveiro were monitored. The city is a medium sized urban area (55,000 inhabitants) (23). All monitored routes, shown in Figure 1, connect the University (located in the city centre and 1.3 km from the N109 and A25 city rings) to a point located in the suburbs (more precisely at the confluence of the N109 and A25 rings). The selection of these points allowed the assessment of three distinct alternative routes. While Route RA is predominantly (56%) driven on motorway A25, Route RB essentially uses the arterial road N109. Finally, Route RC is located entirely in a compact, urban environment. All the routes were tested and analysed separately in both directions, Centre to Suburbs (CS) and Suburbs to Centre (SC), because of the significant distance changes of each way related to traffic constrains.

FIGURE 1 Study routes maps

In order to identify the energy and environmental impacts of route choice at the intercity level, GPS and video data of 4 parallel routes (R1, R2, R3 and R4) were
collected between Aveiro and Oporto. Route R1 extends over 76.8 km (47.7 mi) and it is mostly driven on the A1 motorway. Almost the entire route consists of motorways, and A1 is the only section where there is a toll of 3.15 €. This section has an average daily traffic (ADT) of about 20,000 vehicles (24). Route R2 is 76.6 km (47.6 mi) long and is based on the A29 motorway that runs parallel to the A1. This option is widely used because unlike A1, this motorway currently has no toll. The ADT on A29 ranges from around 33,000 vehicles in the southern sections to 73,000 in the northern sections. There are other distinctive features of A29 such as considerable areas of speed limit of 100 km/h – 62 mph (and not 120 km/h – 74 mph), lower quality of pavement, more curves, and more interchange.

Routes R3 and R4 were mainly performed on arterial routes. Route R3 is the longest, 87.3 km (54.2 mi), in which 34% is made on motorways (connecting the city of Aveiro to the freeway N1 via A25 – 21.5 km (13.4 mi) and 13 km (8.1 mi) before the final destination, via A1 and A20). The freeway N1 runs north through towns and industrial zones with a considerable number of ramps and intersections. However, new 3-lane sections were built in some areas, bypassing intermediate towns. Route R4 is composed of the highway N109 (only 3% near Oporto traverses motorways – ring road A20), which runs along the coast. Since most of the route is travelled through urban areas, Route R4 shows the highest density of intersections and other traffic calming facilities (such as speed reduction humps). Both for N109 and N1, there are currently no monitoring data traffic in the analysed sections. Table 1 summarizes some features of all routes.

**TABLE 1 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 Total</th>
<th>TL</th>
<th>R</th>
<th>On</th>
<th>Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA-CS</td>
<td>6.9</td>
<td>50 (29%), 70 (36%), 120 (58%)</td>
<td>2 (29%), 4 (71%)</td>
<td>11</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>6</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>1</td>
<td>3</td>
<td>2</td>
<td></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>1</td>
<td>5</td>
<td>11</td>
<td>15</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>1</td>
<td>3</td>
<td>9</td>
<td>11</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>3</td>
<td>5</td>
<td>6</td>
<td>5</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>3</td>
<td>5</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>R1</td>
<td>77.1</td>
<td>50 (2%), 90 (7%), 120 (91%)</td>
<td>2 (2%), 4 (82%), 6 (8%)</td>
<td>9</td>
<td>1</td>
<td>3</td>
<td>26</td>
<td>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</td>
<td>2</td>
<td>35</td>
<td>33</td>
</tr>
<tr>
<td>R3</td>
<td>87.2</td>
<td>50 (2%), 50/70 (58%), 90 (7%), 120 (33%)</td>
<td>2 (48%), 3 (12%), 4 (33%), 6 (7%)</td>
<td>135</td>
<td>20</td>
<td>7</td>
<td>48</td>
<td>58</td>
</tr>
<tr>
<td>R4</td>
<td>75.7</td>
<td>50 (23%), 50/70, (68%), 90 (6%), 120 (3%)</td>
<td>2 (88%), 4 (2%), 6 (10%)</td>
<td>275</td>
<td>46</td>
<td>19</td>
<td>47</td>
<td>45</td>
</tr>
</tbody>
</table>

TL – Traffic lights, R - roundabouts

3.2 Emissions estimation – Vehicle Specific Power (VSP) methodology

“Micro-scale dynamic emissions models could be primarily classified into load-based models and regression based models. VSP methodology is an example of the latter. The computational efficiency of this type of models approaches makes them more widely accepted in energy and emissions factors computations in traffic planning projects (25). VSP methodology, which is based on vehicle position coordinates, speed, acceleration and slope, has proven to be very useful in estimating micro-scale emissions in gasoline vehicles (26). Recent research has suggested that VSP method is also applicable for diesel vehicles (14). The methodology based on the VSP variable is explained elsewhere (14). The first step focuses on the calculation of VSP by the following equation:
Where:

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

These terms represent the engine power required in terms of kinetic energy, road grade, friction and aerodynamic drag (14). VSP values are usually grouped in combinations of 1 kW/ton from -50 to +50. In the second step, these values are categorized in modes (from 1 to 14) so that each mode has an average emission rate. For gasoline and diesel vehicles, average emissions rates used in this research can be found elsewhere (14-16).

In order to reflect the Portuguese Fleet as closely as possible, the considered emissions rates are related to LDGV and LDDV with engine sizes smaller than 3.5 and 1.8 L respectively.

4. RESULTS

4.1 Average speed and travel time

In Table 2, the results of travel time and average speed show that, although Route RA is the longest, it is the fastest option allowing travel time savings of 33% and 23% for Routes R3 and R2, respectively. It is also clear that all trips towards the suburbs (CS) are slower than in the direction of the centre (SC). This can be explained by the higher complexity in the configuration of the main intersections in Routes R1 and R2, and the increased distance travelled on one-way streets in Route R3. The travel time standard deviation and T-student confidence intervals suggest that there is more variability of travel time on Route RC. Changes in average speed in relation to alternative drivers and vehicles were not found.

Concerning intercity routes, it is clear that motorway options (Routes R1 and R2) are less time consuming than the alternative routes. Comparing with the closer alternatives, Route R1 allows 32% of time saving in relation to Route R3, and Route R2 saves 47% when compared with Route R4. The travel time standard deviation and 95th percentile confidence interval suggests that Routes R2 and R3 have lower reliability. Particularly due to the higher traffic volume and the lower capacity presented by A29, Route R2 may be more vulnerable to incidents and congestion. Although Route R4 is the shortest route, the travel time is higher than on other routes. However, this route presents more uniform travel times compared with Route R3. With the exception of motorways routes in which DBV1 shows a lower average speed comparing with DAV1 (see R2 column) and the slight reduction of average speed for DAV2 (see R1 and R2), no significant changes were observed.
TABLE 2 Average travel time and speed statistics

<table>
<thead>
<tr>
<th></th>
<th>Urban Routes</th>
<th>Intercity Routes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RA-CS</td>
<td>RA-SC</td>
</tr>
<tr>
<td>Average Travel Time (min)</td>
<td>7.2</td>
<td>5.4</td>
</tr>
<tr>
<td>95 Percentil of Travel Time (min)</td>
<td>7.7</td>
<td>6.0</td>
</tr>
<tr>
<td>5 Percentil of Travel Time (min)</td>
<td>6.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Travel Time Standard Deviation (min)</td>
<td>0.46</td>
<td>0.40</td>
</tr>
<tr>
<td>T-student-Confidence intervals</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td>Average Speed km/h (mph)</td>
<td>56 (35)</td>
<td>63 (39)</td>
</tr>
<tr>
<td>95 Percentil of speed km/h (mph)</td>
<td>62 (38)</td>
<td>68 (42)</td>
</tr>
<tr>
<td>5 Percentil of speed km/h (mph)</td>
<td>53 (33)</td>
<td>58 (36)</td>
</tr>
<tr>
<td>Distance - km (mi)</td>
<td>4.8 (4.2)</td>
<td>5.7 (3.5)</td>
</tr>
<tr>
<td>Number of trips (n)</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Average Speed DAV1 km/h (mph)</td>
<td>56 (35)</td>
<td>63 (39)</td>
</tr>
<tr>
<td>Average Speed DBV1 km/h (mph)</td>
<td>55 (34)</td>
<td>61 (38)</td>
</tr>
<tr>
<td>Average Speed DAV2 km/h (mph)</td>
<td>60 (37)</td>
<td>67 (41)</td>
</tr>
</tbody>
</table>

4.2 VSP Modes

A detailed analysis of time spent in each driving VSP mode for urban and intercity routes was performed. Regarding urban routes, route RC presented the highest predominance of lower VSP modes. About 20% of time was spent on mode 3, indicative of idling, and 90% of time was spent on modes 1 to 7, corresponding to decelerations (1 and 2) and accelerations at lower speed ranges (modes 4 to 7). By contrast, Route RA, showed a balance in the distribution of VSP modes because motorways lead to the occurrence of higher VSP modes (higher speeds and hard accelerations). Route RB demonstrated an intermediate behaviour. 95% t-student confidence intervals showed a lower accuracy in mode 3 (about 3%) due to the natural variability of incidents, such as traffic lights, illegal parking, and congestion, which enhances idling.

In relation to intercity routes, the same trend of urban routes was observed. Routes R1 and R2, performed essentially on motorways, have a more uniform distribution of VSP modes compared with Routes R3 and R4 performed on highways where the reduction of speed shifted the distribution towards lower VSP modes. For highway routes, 7% (R3) and 12% (R4) of time is consumed in idling situations, and just 22% (R3) and 8% of time (R4) is spent on modes higher than 7. By contrast, on motorways routes, 42% (R1) and 38% (R2) of time is spent on modes higher than 7.
4.3 Total emissions

Here, the average total emissions of the monitored routes is discussed, focusing on CO₂, CO, and HC emissions from LDGVs, and NOₓ from LDDVs, the major sources of each pollutant. Figure 2 provides a general description of average emissions according to driver and vehicle.

Regarding CO₂ emissions for urban circuits, no significant changes are observed mainly for routes driven towards city centre (SC). However, in the reverse direction, Route RC presents an average decrease of 11%, compared with Route RA. Since the highest emission rates per distance were verified for this route, the shorter distance is a strong factor for total CO₂ emitted. In relation to intercity trips, the same trend is observed i.e. the faster routes performed on motorways are more environmentally friendly with respect to CO₂ emissions and fuel consumption.

The analysis of total CO emissions suggests that there is a trade-off between the travel time reduction and the minimization of CO emissions. Both urban and intercity routes have shown that a larger amount of CO is emitted if the route leads to fast driving. Although the travel times were approximately the same, a more aggressive driving style of Driver B has increased CO emissions by more than 50% for Route RA towards city centre. Regarding intercity routes, combining a smoother driving style and using a route with lower speeds would enable a two-thirds reduction of CO emissions.

Figure 2(e) shows a comparison of the cumulative profile of CO emissions change, in three situations: (1) DBV1 with congestion; (2) DBV1 without congestion (average speed - 88 km/h - 55 mph); and (3) DAV2 without congestion (average speed - 88km/h – 55 mph). In relation to the congestion situation, a sharp decrease of the grade corresponding to the state of idling, which has extended travel time, is noticed. Although the situation of congestion leads to lower emission rates, the higher travel time causes higher emissions. Regarding the no-congestion situation, the comparison between the cumulative emissions profiles of DBV1 and DAV2 shows a progressive discrepancy until 1700 seconds of travel time. The analysis of the instantaneous speed profiles data, seen in Figure 2 (f), confirms that the major differences occurred during the period where DBV2 was driving at speeds exceeding 110 km/h. (68 mph). The difference is slightly attenuated at the end of the journey due to higher speed of DAV2.

These results corroborate that CO emissions are extremely sensitive to VSP throughout the entire range of acceleration and high speed events.

The emission of NOₓ from LDDVs follow the same trend described above for CO emissions from LDGVs, but with less disparity between the various situations. The slower routes, Routes RC and R4, present average reductions of about 35%, compared with the fastest alternatives. However, for Route RC, the reduction is related with the shortest distance, while for Route R4, the difference lies primarily in the reduction of speed, since the distance is similar to Routes R1 and R2.

In relation to HC emissions in the urban setting, the routes that have shown fewer emissions are Routes RB and RC, with slight variations depending on the travel direction (22% and 15%). Route R4 is the intercity route with the lowest HC values. Although the emission factors per distance for Routes R3 and R4 are quite similar, Route R3 is penalized because it is the longest.

Overall, under uncongested situations, a combination of an appropriate route and smoother driving styles can result in emissions reductions of CO₂-25%, CO-68%, NOₓ-40% and HC-29%. Mainly at intercity scale, quicker routes lead to fuel and CO₂ emissions savings. However, these options may increase considerably emissions of CO (58%), NOₓ (33%) and HC (16%).
FIGURE 2 a) – d) Total emissions for urban and intercity routes, e) accumulated CO emissions and f) speed profile over travel time for two samples.
4.4 Emission rates analysis as function of distance

To analyze rates emission profile, Route R3 was selected as a case study, due to its variability in road characteristics along the route. Thus, this route has been divided into 6 main sections corresponding to the following characteristics:

[1], [5] – Motorway at free flow speed
[2], [4] – 2-lanes highway crossing intermediate villages
[3] – 2/3 lanes highway bypassing intermediate towns
[6] – Motorway with high traffic volume - Oporto Ring

Figure 3 provides an example of speed, altitude and emission profiles for a trip performed on Route R3. In addition to CO$_2$, the focus was on CO emissions from LDGVs and NO$_x$ from LDDVs.

FIGURE 3 a) Speed and altitude profile, b) CO / CO$_2$ average emissions per km and section (LDGV), c) NO$_x$ / CO$_2$ emissions average per km and section (LDDV).
Regarding emissions from LDGVs, a complete opposite behavior in CO₂ and CO emissions is observed. On sections performed on the motorway where CO₂ emissions rates are lower, the amount of CO emitted per kilometer in these sections is considerably higher. The comparison of the slower sections of the highways, seen in sections 2 and 4, shows a slight decrease for both pollutants. Since the average speed is similar, about 45 km/h for both sections, this reduction of emissions is probably due to the downward grade of Section 4. For all paths analyzed, CO emissions rates proved to be strongly dependent on the grade.

Regarding emissions from LDDVs, despite a relative similarity in the curves of average CO₂ and NOx emissions by kilometer, the average emissions by section have opposite behaviours. NOₓ presents a profile similar to CO emissions from LDGVs, showing lower emission rates in the slower sections. In contrast with CO₂ emission rates from LDGVs, the section with lower emissions was Section 3. Sections traveled at moderate speed and with less congestion are more favorable for the reduction of CO₂ emissions from LDGVs.

In summary, it may be concluded that the emission profile vary considerable over the route, strongly depending on the characteristics of each section. An opposite behaviour between emissions of CO₂ and local pollutants, mainly CO was also observed. Sections with higher traffic volume or lower capacity have the highest fuel consumption rates, as evident from the CO₂ emissions.

### 4.5 Statistical analyses

Table 3 presents mean, standard deviation (SD) and standard error of mean (SEM) for total emissions estimated, considering all trips performed during the experiments.

#### TABLE 3 Descriptive statistics for total emissions (g) by route.

<table>
<thead>
<tr>
<th>Route</th>
<th>Urban Routes</th>
<th>Intercity routes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RA CS</td>
<td>RA SC</td>
</tr>
<tr>
<td><strong>CO₂</strong></td>
<td>Mean</td>
<td>1,018,182</td>
</tr>
<tr>
<td></td>
<td>SEM</td>
<td>102,154</td>
</tr>
<tr>
<td><strong>NOₓ</strong></td>
<td>Mean</td>
<td>43</td>
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<tr>
<td></td>
<td>SEM</td>
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<td><strong>CO</strong></td>
<td>Mean</td>
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<td></td>
<td>SEM</td>
<td>227</td>
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<tr>
<td><strong>HC</strong></td>
<td>Mean</td>
<td>80</td>
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<tr>
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<th>Intercity routes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RA CS</td>
<td>RA SC</td>
</tr>
<tr>
<td><strong>CO₂</strong></td>
<td>Mean</td>
<td>1,203,774</td>
</tr>
<tr>
<td></td>
<td>SEM</td>
<td>120,549</td>
</tr>
<tr>
<td><strong>NOₓ</strong></td>
<td>Mean</td>
<td>847</td>
</tr>
<tr>
<td></td>
<td>SEM</td>
<td>133</td>
</tr>
<tr>
<td><strong>CO</strong></td>
<td>Mean</td>
<td>422</td>
</tr>
<tr>
<td></td>
<td>SEM</td>
<td>133</td>
</tr>
<tr>
<td><strong>HC</strong></td>
<td>Mean</td>
<td>295</td>
</tr>
<tr>
<td></td>
<td>SEM</td>
<td>32</td>
</tr>
</tbody>
</table>
With the exception of route RC, SEM values are in general about 10% of mean. The high deviations on route CR are due to its short distance and intrinsic variability of the route (high number of intersections and traffic lights).

An ANOVA analysis was also performed in order to assess the statistical significance of the descriptive variables (route, driver and vehicle) in regards to emission rates and average speed shown in Table 4. This comparison was performed considering all trips performed for both urban and intercity routes, taking into account the effect of different driver (A and B) and vehicle (1 and 2). The adjusted R² parameter is an indicator of the ANOVA results. Table 4 shows that R² values vary from 0.72 to 0.99, which means that the factors incorporated in ANOVA are suitable and significant to describe the variability in emission rates or average speed. Route is the most important factor connected with emissions and speed. However, CO emissions from gasoline engines and NOₓ emissions from diesel engines reveal to be strongly dependent on the driver profile. CO₂ emissions from both types of engines and HC emissions from diesel engines are not statistically significant with respect to driver (P values> 0.05, shaded in gray). Average speed is confirmed to be independent of both vehicle and driver.

Although the vehicle type is less significant than route with respect to variability in emission rates, all the pollutant emission rates showed a strong relationship with vehicle. Since average speed, and hence travel time, have demonstrated to be independent of the driver and vehicle, this dependency should be a consequence of vehicle characteristics on driving behaviour affecting the profile of accelerations and decelerations. The presence of an automatic gearbox in Vehicle A and a manual transmission in Vehicle B could help explain such variations.

### Table 4 ANOVA results: F-values and P-values for pollutant emissions in relation to route, driver and vehicle.

<table>
<thead>
<tr>
<th></th>
<th>Route</th>
<th>Driver</th>
<th>Vehicle</th>
<th>Adjusted R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>F 18.0</td>
<td>0.0</td>
<td>11.6</td>
<td>0.718</td>
</tr>
<tr>
<td></td>
<td>P 0.000</td>
<td>0.988</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>F 47.5</td>
<td>9.5</td>
<td>7.7</td>
<td>0.861</td>
</tr>
<tr>
<td></td>
<td>P 0.000</td>
<td>0.003</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>NOₓ</td>
<td>F 54.8</td>
<td>32.9</td>
<td>17.6</td>
<td>0.879</td>
</tr>
<tr>
<td></td>
<td>P 0.000</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>F 35.8</td>
<td>1.4</td>
<td>15.8</td>
<td>0.848</td>
</tr>
<tr>
<td></td>
<td>P 0.000</td>
<td>0.236</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>F 56.9</td>
<td>0.6</td>
<td>14.5</td>
<td>0.883</td>
</tr>
<tr>
<td></td>
<td>P 0.000</td>
<td>0.423</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>F 139.5</td>
<td>87.8</td>
<td>10.3</td>
<td>0.947</td>
</tr>
<tr>
<td></td>
<td>P 0.000</td>
<td>0.000</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>NOₓ</td>
<td>F 23.0</td>
<td>13.1</td>
<td>13.1</td>
<td>0.749</td>
</tr>
<tr>
<td></td>
<td>P 0.000</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>F 24.8</td>
<td>16.2</td>
<td>22.3</td>
<td>0.807</td>
</tr>
<tr>
<td></td>
<td>P 0.000</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>Av. Speed</td>
<td>F 1139.0</td>
<td>0.1</td>
<td>0.0</td>
<td>0.807</td>
</tr>
<tr>
<td></td>
<td>P 0.000</td>
<td>0.823</td>
<td>0.852</td>
<td>0.993</td>
</tr>
</tbody>
</table>
4.6 Routes classification

A general rating of indicators for all routes is presented (Table 5) and discussed. The table is divided between the parameters that are usually available to the drivers, such as travel time, distance, and cost, and other parameters that were analyzed during this research and may be disseminated through ATIS. The classification related to emissions assigned in Table 5 was constructed considering the global average of total pollutant emissions, shown in black bars of Figure 2.

TABLE 5 Route rating according GPS/videotape monitoring and estimated total emissions

<table>
<thead>
<tr>
<th>Routes</th>
<th>RA CS</th>
<th>RA SC</th>
<th>RB CS</th>
<th>RB SC</th>
<th>RC CS</th>
<th>RC SC</th>
<th>Intercity routes</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel time</td>
<td>**</td>
<td>*****</td>
<td>**</td>
<td>***</td>
<td>o</td>
<td>*</td>
<td>**</td>
<td>****</td>
<td>****</td>
<td>**</td>
<td>o</td>
</tr>
<tr>
<td>Distance</td>
<td>o</td>
<td>*****</td>
<td>o</td>
<td>****</td>
<td>o</td>
<td>****</td>
<td>o</td>
<td>****</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Cost</td>
<td>o</td>
<td>*****</td>
<td>o</td>
<td>****</td>
<td>o</td>
<td>****</td>
<td>o</td>
<td>****</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
</tbody>
</table>

| T. Time Variability | ***** | **** | ** | o | ** | **** | o | o | ** | o | o |
| Preservation       | ****  | ***** | ** | o | o | ****  | o | **** | ** | o | o |
| # Singularities    | ****  | ***** | ** | o | o | ****  | o | **** | ** | o | o |
| Incidents          | ****  | ***** | ** | o | o | ****  | o | **** | ** | o | o |
| CO₂ Emissions      | o     | ****  | *** | **** | o   | ****  | o | **** | ** | o | o |
| CO Emissions       | o     | ****  | o   | **** | o   | ****  | o | **** | ** | o | o |
| NOₓ Emissions      | o     | ****  | o   | **** | o   | ****  | o | **** | ** | o | o |
| HC Emissions       | o     | ****  | o   | **** | o   | ****  | o | **** | ** | o | o |

* Worst ***** Best

Regarding urban routes, the ratings shown in Table 4 reveal that all journeys made in the CS direction are longer than in the reverse direction. This difference in distance gives an advantage to routes driven in the SC direction for almost all categories. Route RA is clearly advantageous in terms of travel time, reliability (travel time variability), and quality of infrastructure, but demonstrates worse results for emissions. Although route RC shows the worst indicators in the fields of travel time and overall quality, its short distance leads to an advantage for total emissions. Route RB presents a compromise on minimizing emissions and the overall infrastructure quality.

For the intercity routes examined, the different rated parameters in Route R1 have established a fairly regular pattern. This route is competitive for almost all categories as evidenced by the fact that in 7 of 11 parameters obtains four or five stars, replicating the advantages of using the motorway: high quality of the pavement, no traffic lights and no roundabouts, high speed of the journey, and high reliability. Moreover, this route presents the lowest CO₂ emissions. By contrast, HC, NOₓ, and particularly CO emissions present the highest values. Toll payments are also a major disadvantage of this route.

Route R2, which is also largely driven on motorway, presents almost the same advantages described for Route R1. Furthermore, this route also provides a key benefit in terms of cost since it has no tolls. However, compared to other alternatives, Route R2 is the route with greater variability of journey times justified by the higher volume of traffic and rates of road accidents. The Portuguese Road Safety Authority has demonstrated that the section of A29 included in Route R2 has the highest rates of road accidents in Portugal, presenting two accident black-spots. Like Route R1, this route presents good ratings for CO₂, and poor classification for the other pollutants.
Route R3 gets an intermediate classification, meaning that is better option than Route R4, but a worse choice than the alternative motorway routes. Route R4 is advantageous from the standpoint of distance and on minimizing emissions of CO, HC, and NOx. For CO2 emissions and fuel consumption, Routes R3 and R4 are worse solutions.

In summary, there is a tradeoff between the reduction of CO2 and other pollutant emissions. Moreover, the routes that reduce CO, HC, and NOx emissions are those that present unfavorable characteristics to the drivers, such as slower speeds, a greater number of crossings, poor quality of pavement, and a high density of incidents.

5. CONCLUSIONS

This paper contributes by providing an assessment of pollutant emissions from light duty diesel and gasoline vehicles for urban and intercity routes. Other factors that may influence route choice, such as distance, cost, travel time, infrastructure quality, and occurrence of incidents, have been analyzed. Based on collected data from the characterization of different routes, this work has established a classification system of competing pathways.

ANOVA tests have demonstrated that route choice is the most significant aspect regarding the emission rates of the analyzed pollutants. The selection of appropriate routes can mean savings of 20% in fuel consumption and consequent CO2 emissions. However, there is a tradeoff between CO2 and CO, HC and NOx emissions minimization. For example, the choice of an intercity CO2 saving route can dramatically increase emissions of CO (58%), NOx (33%) and HC (16%). In general, quicker routes with less congestion proved to be better alternatives for the reduction of fuel consumption and CO2 emissions. The decrease of speed was shown to be a positive factor in minimizing local pollutant emissions. Overall, due to the complexity of issues involved, e.g., non-linear relationships between emissions and driving patterns-speeds, stops, etc., it is difficult to identify a single dominate route that will be best from an emissions perspective.

In urban routes at off-peak hours, the shorter distances proved to be a key factor in reducing emissions for all pollutants. Driver behavior showed to be particularly decisive in the amount of CO and NOx emitted. Besides the potential to reduce pollutants associated with appropriate route choice, there is also potential to reduce emissions based on the drivers’ awareness of ecodriving.

A question arises when imagining that all drivers have access to information on emissions and that everyone would choose the more environmentally friendly route: Would air pollution increase? Firstly, this may not happen due to heterogeneity in people’s responses. Secondly, since the results of this study are related to off-peak hours, there is sufficient capacity to accommodate demand.

In the future, it would be interesting to analyze the same routes during peak traffic times to assess if significant changes are observed. Since tolls will be introduced on the A29 section of Route R2, it would be important to assess the consequences of this measure in terms of total network emissions.

Drivers’ behavior can be changed in two ways: a) Providing information and b) implementing legal mechanisms or taxes that lead to change people’s actions. The authors believe that by providing additional information, there will be a sector of the population who will follow more environmentally friendly routes, when their personal costs are not excessively affected. However, to test this hypothesis, future research
should also focus on providing the generated information to travelers and examining their travel choices, using stated and revealed route selection behavior.

ACKNOWLEDGMENTS

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