TITLE: MEASURING THE EFFECTS OF TRAFFIC CONGESTION ON FUEL CONSUMPTION

SUBMISSION DATE: 11 November 2014.

WORD COUNT: 3,998 (without references) + (7 figures + 5 tables) x 250 = 6,998

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ABSTRACT

Nowadays, road transportation sector is responsible for a considerable amount of the total energy consumption, also contributing to about 20-30% of the total man-made CO₂ emissions worldwide.

In metropolitan areas, the problem is compounded by the effect of traffic congestion. Transport models, online route planners, and the latest versions of on-board navigators do take into account traffic variability in their calculation of travel times. However, the effect of traffic congestion on fuel consumption is hardly taken into consideration, thereby introducing a considerable distortion in the result and consequently, the traveler decision process.

The aim of this paper is to investigate in detail, how traffic congestion affects fuel consumption and to evaluate the importance of including traffic congestion in modeling and driver information systems. This analysis is based on empirical data collected from some itineraries of a metropolitan motorway and streets of the metropolitan area of Madrid, Spain. Specifically, a total of 3,800 trips were recorded with three vehicles under different traffic conditions and driving styles. The results show considerable increase in fuel consumption under congested traffic conditions compared with free flow conditions, but also points to the differences depending on the type of itinerary.

Keywords: Congestion, Fuel consumption, Route planner, Navigator, Energy, CO₂
1. INTRODUCTION

The emission of greenhouse gases (GHG) and excessive consumption of energy resources is a global problem, due to both, its causes and consequences (1). The transport sector is one of the largest emitters despite the advances in the field of engines technology.

According to statistics provided by the European Environment Agency (2), road transportation sector has begun to reduce their emission of GHG; but still contributes to about 93% of the emissions attributable to the transportation sector representing approximately 20.4% of the total emission. In the U.S., the contribution percentage of road transportation to total GHG emissions is even higher, reaching almost 22% (3). In terms of energy consumption, the transportation sector accounted for 26% of the global energy consumption in 2010, and transportation energy use is expected to increase by 1.1 percent every year from 2010 to 2040, according to the International Energy Outlook 2013 Reference case (4).

It is worth mentioning that a great amount of fuel consumption and GHG and pollutants emissions from road transportation sector are concentrated in metropolitan areas. In fact, according to the European Environmental Agency, metropolitan areas account for 40% of the total CO2 produced by the road transportation sector (5).

In this context, many efforts to reduce energy consumption focus on the road transport sector. The European Commission (6) proposes an integrated policy to tackle the problem from different directions, among them, worth to mention are: the demand management, the shift to cleaner modes, improving vehicle technologies, and the use of information and communication technologies (ICT).

2. ARE CONGESTION EFFECTS ON CONSUMPTION PROPERLY CONSIDERED?

Section 2 presents a review of different models and driver information systems with regard to congestion treatment. It is divided into 3 parts. The first part discusses the most remarkable features of route planners and navigators. The second part summarizes how congestion is treated in transportation demand models, finishing with some remarks about emission models and the disadvantages of using average speed models at micro scales.

2.1 Cost Calculations in Route Planners and Navigators

An online route planner provides information on optimal routes based on different parameters. Usually, it suggests the shortest or fastest route based on complex algorithms developed by Dijkstra (7), but many of them take also into account other factors, such as speed limits, safety and even the current traffic situation.

For instance, in the case of Google Maps (8), it displays the optimal route and estimated travel time, according to the traffic situation and congestion level. In its first version, this option was based on historical data, while nowadays it computes utilizing data extracted from the instantaneous position of smartphone users. Moreover, these applications also provide an estimate of fuel consumption for the selected route, allowing the user to select from general categories of vehicles or to define the average consumption. Mappquest (9) calculates the cost of journey using the average price of gas along the route, length of trip, mileage of the vehicle, and route characteristics. In other websites, the user can also customize route characteristics: shortest journey time, shortest distance or the most fuel-efficient route (10). However, none of these online route planners take into consideration the traffic conditions to calculate fuel consumption.

Quite similar is the functioning of the GPS navigation systems, which are able to recalculate and guide the user through a faster route in case of congestion. However, the fastest...
route is not always the one with the lowest fuel consumption (11). Hence, in recent years, "eco-routing" algorithms have been developed to inform the user about the most economical and lower emissions route (12), although very few methodologies integrate real time emissions and traffic information (13).

2.2 Congestion Costs in Transportation Demand Models

Demand models in transportation use a generalized cost function while distributing trips between different modes and alternative routes. These cost functions include both monetary and non-monetary costs; basically travel time.

Generally, fuel consumption is added in the formulas of generalized cost as a function of travel distance, which may be a good enough approximation if static traffic conditions are taken into consideration. To estimate environmental externalities and test congestion pricing policies, some studies also consider average speed as a factor to include environmental costs in the model (14). With these algorithms, traffic variability is taken into account; but the use of emission models based on the average speed can result in erroneous estimates depending on the type of route, as discussed in the following section.

2.3 Traffic Congestion in Energy and Emission Models

The energy and emission models are usually developed from a large number of measurements made, both in laboratories and field trips. These models usually emphasize the importance of the fleet composition and, depending on the level of detail, these vehicles are aggregated into categories with similar values of consumption and emission.

The fuel consumption and emission models can be classified according to their level of disaggregation. They range from the very detailed ones based on the speed profiles of each vehicle to the aggregate ones used for national emissions inventories.

After examining some emission models, Smit et al. (15) concluded that most of them do explicitly consider the traffic situation in the modeling process. However, the main problem lies in the use at a local scale of models designed for emission inventories at regional or national level, as their improper use can lead to serious over- or underestimations.

Macro-level models are applied for the analysis of large networks. In this family of models, the average speed models consider the average speed, traffic demand, and fleet composition of each itinerary to estimate emissions and fuel consumption. Examples of this type of models are MOBILE (16) and COPERT (17).

Average speed is considered as a key factor in fuel consumption and CO2 emissions. However, from a traffic engineering point of view, the average speed itself does not sufficiently explain the variability of traffic conditions and its implications (11). For example, an average speed of 40 km/h in an arterial road with traffic light coordination could reflect free-flow conditions, achieving an almost constant speed. The same average speed on a motorway section can represent high congestion levels, which has clear implications on fuel consumption and emissions. Figure 1 shows the speed profiles of two trips made with the same vehicle and with a similar average speed in two different itineraries. However, the differences in traffic conditions lead to an increase in fuel consumption of about 40% for the congested section.
3. OBJECTIVES AND METHODOLOGY

The literature review shows that the effects of congestion on fuel consumption are treated very differently depending on the objectives of the model. In the very detailed micro-level models, the influence of congestion is treated directly while at macro level, only a few models enable analysts to incorporate local driving patterns which reflect congestion (18).

Under these premises, the aim of this paper is to investigate in detail how traffic congestion affects the consumption and to evaluate the importance of considering traffic congestion in modeling processes and in driver information systems. This analysis was performed on different roads within the metropolitan area of Madrid with the objective to analyze the differences between urban motorways and urban street itineraries.

As detailed below, the methodology is based on the analysis of fuel consumption and speed profiles collected by floating vehicles which performed a number of trips in the city of Madrid.

3.1 Data Collection Campaign

The data collection campaign was developed under the framework of the European research project "ICT-Emissions", which aims to develop a methodology to simulate in detail the effects on GHG emissions of a number of ICT measures applied to road transportation. As an added value of this project, it is also intended to validate the methodology with case studies conducted in the partner cities of Rome, Turin, and Madrid. In each of these cases, data collection campaigns (induction loops, cameras, floating cars, etc.) were conducted with the aim of evaluating the evolution of traffic and other vehicle parameters before and after the implementation of the ICT measures.

In March and April 2013, the data collection campaign took place in coordination with the Department of Traffic Technologies of Madrid. The main objective was to obtain speed profiles and fuel consumption data at various itineraries of the M30 ring motorway (itineraries 1, 2, 3, and 4) and some adjacent urban streets (itineraries 5, 6, and 7) (Figure 2). Urban itineraries do not include arterials, but only local streets and signalized collectors.
FIGURE 2 Monitored itineraries in the data collection campaign in Madrid.

This data collection campaign consisted of conducting a representative number of trips through the selected itineraries using floating cars (FCD). With this procedure, it is possible to obtain the fuel consumption and speed profiles. Three FIAT passenger cars were involved in this study, a Punto 1.2L gasoline and two diesel variants, Punto and Bravo, with 1.3L and 1.6L engines, respectively. The number of drivers involved was 9 and the total number of recorded trips was approximately 3,800.

The vehicles were equipped with a mobile device with GPS connection to collect data on distance travelled, instantaneous position, and speed at a frequency of 1 Hz, thus enabling to record speed and acceleration profiles. The average fuel consumption (in L/100km) was recorded directly from the on-board display at the end of each itinerary.

3.2 Review and Selection of Traffic Congestion Indicators

Due to the availability of data and the nature of demand models, the most commonly used indicator has been the volume-to-capacity ratio, although this indicator has a number of shortcomings when analyzing traffic congestion in detail (19). The main issue is that drivers, in general, ignore this kind of information, but rather give importance to travel times.

Based on the literature review (20-23) and trends in software and application developers, the following congestion indicators are highlighted:

- **Delay**: Difference between current travel time and free flow travel time
- **Delay rate**: Difference between current travel time and free flow travel time per kilometer
- **Congestion Index (CI)**: Ratio between travel time and free flow travel time
- **Speed reduction congestion index (SRCI)**: Mean speed reduction from free-flow to current conditions over free flow mean speed. Index normalized to a 0 to 10 scale.
- **Tom Tom congestion index**: Difference between current travel time and free flow travel time over free-flow travel time.
Level of Service (LOS) is a qualitative measure of the quality of driving conditions. On a scale of A to F, it describes a range of flow conditions where A represents free-flow conditions; and F severe congestion.

This study will analyze the traffic congestion using the delay rate. On one hand, from the point of view of drivers, delay is the most understandable and interesting indicator, as it reflects the time lost in congestion. The use of a length ratio makes possible the comparison between sections with similar characteristics but different length.

3.3 Data Processing

As mentioned before, the data collection campaign was performed in the framework of the “ICT-Emissions” research project, which includes testing some traffic management measures, such as variable speed limits and section speed control. For the purpose of this study, the trips on which these measures were in practice were not considered, as they could distort the fuel consumption and travel time results.

Once filtered and rejected some trips due to GPS reception failures, the remaining were grouped by vehicle and itinerary. The total number is 2,412, distributed as specified in Table 1 and following the itinerary ID number set in Figure 2.

<table>
<thead>
<tr>
<th>Itinerary number and vehicle</th>
<th>M30 ring Motorway itineraries</th>
<th>Urban itineraries</th>
<th>Total per vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Length (km)</td>
<td>5.8</td>
<td>5.3</td>
<td>5.4</td>
</tr>
<tr>
<td>Fiat Bravo 1.6D</td>
<td>72</td>
<td>124</td>
<td>46</td>
</tr>
<tr>
<td>Fiat Punto 1.3D</td>
<td>104</td>
<td>215</td>
<td>72</td>
</tr>
<tr>
<td>Fiat Punto 1.2G</td>
<td>103</td>
<td>172</td>
<td>70</td>
</tr>
<tr>
<td>Total per itinerary</td>
<td>279</td>
<td>511</td>
<td>188</td>
</tr>
</tbody>
</table>

The delay rate is calculated using the following formula for each trip:

\[
DR = \frac{(t-t_0)}{60} \cdot l
\]  

where,

\( t = \) current travel time (s)

\( t_0 = \) free flow travel time (s)

\( l = \) length of itinerary (km)

The fastest trip of each itinerary was set as the free flow travel time of that itinerary. For these reason, specific peak-off measurements were performed with low traffic intensities, although overnight hours were not considered. The selected reference trips where investigated in detail to confirm the absence of any reception failure or anomalous driving behavior.

Measurements of ring motorway trips have been grouped, according to the levels of service (LOS) defined by the AAHSTO (24). Since most of the registered trips are close to the area of flow instabilities (when congestion is about to start) and to achieve more accuracy,
service levels A and B have been divided equally into three sublevels, C and D into two, while E and F are kept as a unique level of service.

4. RESULTS. FUEL CONSUMPTION AS A FUNCTION OF DELAY RATE

After calculating the delay and consumption values following the methodology proposed in the previous section, the trips have been filtered by itinerary and vehicle, obtaining the relation between the delay rate and fuel consumption, both graphically and analyzing best fitting curve. The following paragraphs discuss some of these relations.

4.1 Fuel Consumption and Delay Rate of Urban Motorway Itineraries

In the case of itineraries of M30 Ring Motorway, the graphs show a growing trend of fuel consumption due to the increase in the level of congestion. As an example, Figure 3 shows graphically the relation between fuel consumption and delay rate for the same vehicle on two different itineraries; values grouped by level of service.

![Figure 3](image)

**FIGURE 3** Relation between fuel consumption and delay rate - Example of two itineraries in M30 Ring Motorway.

Thus, for every vehicle and itinerary, the regression can be obtained that best fit the consumption values as a function of the delay rates. Table 2 shows the slopes of the regression lines.

<table>
<thead>
<tr>
<th>Itinerary number and vehicle</th>
<th>M30 ring Motorway itineraries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Fiat Bravo 1.6D</td>
<td>Slope 0.8388</td>
</tr>
<tr>
<td></td>
<td>R² 0.71</td>
</tr>
<tr>
<td>Fiat Punto 1.3D</td>
<td>Slope 0.5549</td>
</tr>
</tbody>
</table>

**TABLE 2** Slope and Goodness-of-Fit of the Regression Line for each Motorway Itinerary and Vehicle
We would expect all the slopes to be positive but, surprisingly, itinerary 3 presents declining fuel consumptions as the delay rate increases. This can be explained by the fact that high levels of congestion were not experienced in this itinerary, so that increase in delay does not involve braking and acceleration phenomena. The delay in this case, is due to mere slight reduction in the current average speed compared to free flow conditions. When only the service levels close to the free flow (LOS A and LOS B) were analyzed, the regression lines present mostly negative slopes, as reflected in Table 3.

**TABLE 3: Slope and Goodness-of-Fit of the Regression Line in Service Levels and Sublevels A and B, for each Itinerary and Vehicle**

<table>
<thead>
<tr>
<th>Itinerary number and vehicle</th>
<th>M30 ring Motorway itineraries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Fiat Bravo 1.6D</td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>-1.3797</td>
</tr>
<tr>
<td>R²</td>
<td>0.40</td>
</tr>
<tr>
<td>Fiat Punto 1.3D</td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>-2.0475</td>
</tr>
<tr>
<td>R²</td>
<td>0.93</td>
</tr>
<tr>
<td>Fiat Punto 1.2G</td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>-6.076</td>
</tr>
<tr>
<td>R²</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Consequently, figure 4 shows the graphs of the same itineraries presented in Figure 3, but considering only LOS A and LOS B. We can observe high values of R² when the slope is negative, but very low in case of positive or nearly horizontal regression lines.

Adjusting to a second degree polynomial, we obtain the following values of goodness-of-fit (R²):

**TABLE 4: Goodness-of-Fit of the second degree polynomial in Service Levels and Sublevels A and B, for each Itinerary and Vehicle**

<table>
<thead>
<tr>
<th>Itinerary number and vehicle</th>
<th>M30 ring Motorway itineraries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Fiat Bravo 1.6D</td>
<td></td>
</tr>
<tr>
<td>R²</td>
<td>0.94</td>
</tr>
<tr>
<td>Fiat Punto 1.3D</td>
<td></td>
</tr>
<tr>
<td>R²</td>
<td>0.93</td>
</tr>
<tr>
<td>Fiat Punto 1.2G</td>
<td></td>
</tr>
<tr>
<td>R²</td>
<td>0.99</td>
</tr>
</tbody>
</table>

As expected, second degree polynomial achieves a better goodness-of-fit, obtaining this way a curve with a minimum for delay rate values between 0.05 and 0.10. Examples are shown in Figure 4.
Analysis of Fuel Consumption with Reference To the Homogeneity of the Speed Profile

In order to investigate the reason for the occurrence of minimum in consumption, it is necessary to analyze an indicator that reflects the speed homogeneity along an itinerary. Thus, Garcia-Castro and Monzon (25) define Positive Accumulated Acceleration (PAA) as an indicator obtained from the analysis of the speed profile in an itinerary which graphically represents the area under the positive accelerations curve. Thus, a trip in which the speed varies considerably tends to have a comparatively much greater PAA value than those of other trips on the same itinerary but with uniform speed.

FIGURE 4 Fitting curve of fuel consumption for delay rates close to free flow conditions (LOS A and LOS B).

FIGURE 5 Example of Positive Accumulated Acceleration and fuel consumption as a function of delay, for an itinerary of M30 urban motorway.
Analyzing where the minimum of fuel consumption and PAA curves are situated in the plot, it is possible to set 3 different areas as a function of the delay rate (Figure 5).

For delay rates close to zero, fuel consumption decreases because the average speed also drops while maintaining a homogenous speed along the itinerary.

In the second zone, increase in traffic intensities lead to instabilities producing increasing braking and acceleration, consequently decreasing the average speed. When the minimum is reached, the average speed reduction is not enough to counter the effect of acceleration-braking process on fuel consumption.

Finally, in the third stage, fuel consumption increases since both the negative effects of increasing accumulated acceleration and the fact that at those high speeds the vehicle no longer lies in the area of maximum efficiency.

### 4.2 Fuel Consumption and Delay Rate in Urban itineraries

For urban itineraries, it was not necessary to group the values based on LOS, as the slopes of the regression lines show consistent and linear tendencies, and the trips recorded are well distributed among the whole range of traffic conditions. Table 5 shows the slope of regression lines for every urban itinerary and vehicle. It is remarkable that the vehicle with a higher engine displacement presents consistently a larger slope for each of the urban itineraries studied. Graphically, this fact can be also observed in the examples shown in Figure 6.

**TABLE 5 Slope and Goodness-of-Fit of the Regression Line for each Urban Itinerary and Vehicle**

<table>
<thead>
<tr>
<th>Itinerary number and vehicle</th>
<th>Urban itineraries</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>5</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Fiat Bravo 1.6D</td>
<td>Slope 1,514</td>
<td>1,0353</td>
<td>1,3394</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R^2$ 0.34</td>
<td>0.40</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>Fiat Punto 1.3D</td>
<td>Slope 1,3506</td>
<td>0.6922</td>
<td>1,0964</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R^2$ 0.38</td>
<td>0.12</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>Fiat Punto 1.2G</td>
<td>Slope 1,4401</td>
<td>0.9041</td>
<td>1,1746</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R^2$ 0.50</td>
<td>0.44</td>
<td>0.62</td>
<td></td>
</tr>
</tbody>
</table>
FIGURE 6  Fuel consumption as a function of the delay rate in urban itinerary 5.

In contrast to the motorway itineraries analyzed in the last section, it is not possible to observe a decrease in consumption with increasing delay rates. This is in line with the fact that for the range of speeds in urban itineraries, a drop of the average speed on an itinerary always involves an increase in fuel consumption following the performance curves of vehicles’ engines (26). In urban areas, both consumption and cumulative positive acceleration (PAA) behave linearly, as opposed to what was observed in the case of urban motorways (Figure 7).

5. CONCLUSIONS
It has been observed that the congestion effects on fuel consumption are not taken into consideration in some route planners and transport demand models. However, the results of the case study presented in this paper show a clear relationship between congestion and fuel consumption. In the case of urban motorways as the case of M30 in Madrid, the data collected show that small increases in traffic starting from free flow conditions are positive in terms of fuel economy, but the general trend is that congestion increases fuel consumption.

Thus, for each itinerary of motorway it is possible to achieve optimum fuel consumption as a function of the delay rate. Once this optimum is exceeded, increasing traffic intensities cause speed profiles to become less homogeneous, and hence increases consumption.

On the other hand, the data analysis in urban areas presents a different behavior. For the speed range analyzed in these areas, fuel consumption increases linearly as a function of congestion.

The analysis of the speed profile homogeneity reveals that the fuel consumption largely depends on the point at which increasing traffic intensities cause flow instabilities. Hence, the optimum is reached at a different point depending on the type of road.

Therefore, the need to include a congestion parameter in fuel consumption models is obvious, since the increase due to the level of traffic can exceed 100%. Moreover, the use of a single indicator (usually average speed) involves some risk, since the optimal fuel consumption depends also on the accumulated acceleration in the section, i.e., speed homogeneity. Similar average speeds do not mean similar fuel consumptions for different types of roads.

For greater accuracy in the calculation of fuel consumption without resorting to microscopic models which require very detailed data, it would therefore be advisable to adjust the average speed models by adding a factor of congestion or traffic homogeneity based on the type of road. Heavy duty vehicles should also be object of further research, as they are major contributions to CO₂ emissions, especially in interurban itineraries.

ACKNOWLEDGMENT

This work was supported in part by the European Commission under the ICT-Emissions project, "Development of a methodology and tools for assessing the impact of ICT measures in road transport emissions". The authors also acknowledge the collaboration of the City of Madrid and Madrid Calle-30.

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