Limits of Applicability of COPERT Model to Short Links and Congested Conditions

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Abstract

The main aim of this study was to identify the limits within which the COPERT model can be reliably applied, with respect to minimum road length and maximum congestion level. This was made possible by comparing the COPERT emission factor trends with the fuel consumption of two passenger cars operating on real-world conditions. The experiment was conducted in an urban corridor ("Corso Lecce" in Turin) and on an urban highway ("M30" in Madrid). The consumption of vehicles was calculated by introducing their driving pattern in validated vehicle models developed with the AVL CRUISE software. There is a good agreement between COPERT and AVL CRUISE relative fuel consumption differences over a reference condition in most of the driving situations examined. However, the agreement degrades when moving to high saturation and short road distances. As general guidance, COPERT reliability increases as the link length increases above 400 m and the saturation level drops below 80%. If shorter distances need to be modelled at a macro level, then it would be safer to aggregate short links to larger conglomerates. Also, specific congestion corrections would be necessary for congestion levels when saturation exceeds approximately 80%.

Introduction

A number of models and methods have been developed over the last 20 years to calculate road transport emissions (Boulter et al., 2007; Smit et al., 2010; Alkafoury et al., 2013; Kousoulidou, et al., 2013). Among these tools, the COPERT software (Ntziachristos et al., 2009) is widely used throughout the Europe for calculating fuel consumption and emissions from various road vehicles. It estimates emission and consumption factors on the basis of continuous functions of the average travelling speed. This is an easy and straightforward method to use, however, it may not offer the necessary detail for specific driving situations (Barlow and Boulter, 2009). Such specific situations may be encountered under highly saturated conditions (e.g. stop-and-go) or for short travelling distances. The aim of this study was to identify the limits, within which the COPERT model can be reliably applied, with respect to minimum road length and maximum congestion level.

We were therefore interested in exploring whether COPERT, with its average speed approach, can satisfactorily be connected at a link-level with traffic macro models. In such an approach, the average speed is not the momentary speed of the vehicle, but the mean speed over a complete driving sequence. The emission factors in COPERT were built by assigning, to the extent possible, representative driving conditions for each average speed bin (Ntziachristos and Samaras, 2013). However, when applying the model to a link level, the actual driving pattern in the link may be very different than the driving patterns considered in developing COPERT emission factors for the same speed. In such a case, the emission factor value estimated from COPERT might not be representative of the actual condition. This is a common question regarding COPERT applicability from many of its users around the world.

In order to examine the limits of applicability of the COPERT method, we setup a real-world experiment, utilizing two traffic sites monitored by the ICT-Emissions project (http://www.ict-emissions.eu). One of each is located in Turin (urban corridor) and Madrid (urban ring-road). Emissions for the particular traffic sites have been modelled at a macro level with COPERT (average speed) and at micro-level, using second by second speed profiles of real vehicles, with AVL CRUISE (https://www.avl.com/cruise1). The general trends of the COPERT expressions were then compared with measured and micro-simulation results and conclusions on the applicability of the average speed approach have been reached. The following sections describe in detail the approach followed in this validation exercise.

Methodology

The main concept in this study was to compare the fuel consumption calculated by COPERT using the average speed approach with simulated information on the exact driving profile that the average speed corresponds to using the AVL CRUISE micro-simulator. This concept is graphically summarized in the flowchart of Figure 1. The measured and simulated data from various traffic conditions retrieved from two sites at both Turin and Madrid were used as input. This approach was conducted for two different passenger car categories, one gasoline and one diesel.

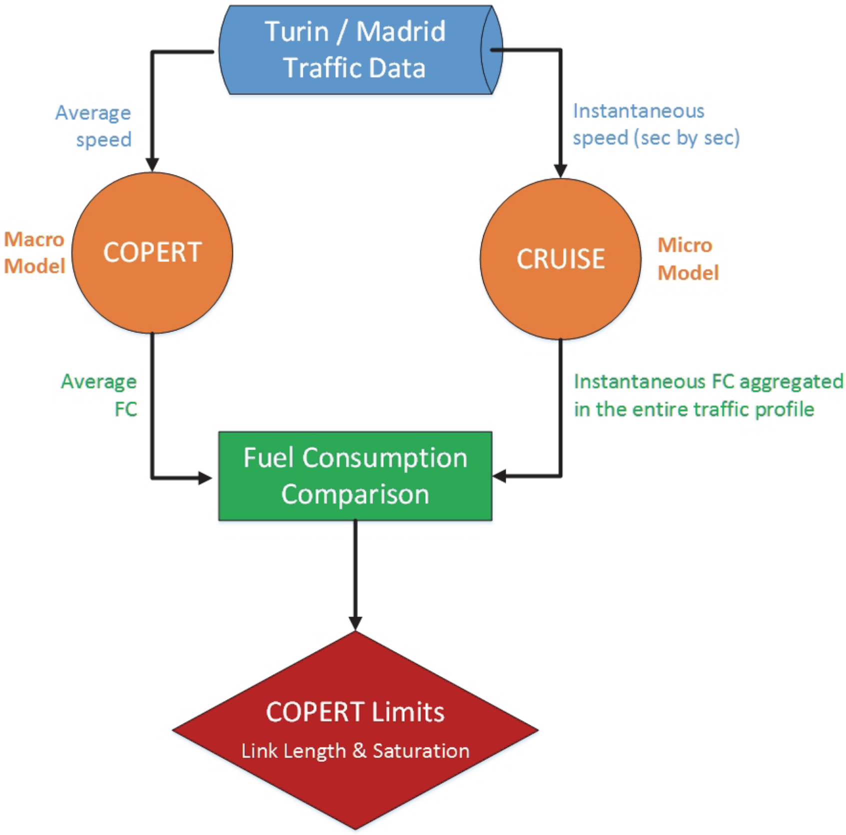

Figure 1: Flowchart of the methodology.

For each traffic condition the fuel consumption was calculated using two different methods:

1. The average speed of each traffic condition was inserted in COPERT 4 (V10.0) and the average fuel consumption was calculated for the two vehicle categories – gasoline 0.8 – 1.4 l Euro 5 and diesel 1.4 – 2.0 l Euro 5.
2. The instantaneous speed profile of each traffic condition was inserted in the corresponding CRUISE vehicle models and the instantaneous fuel consumption was calculated, which then was integrated over the entire driving profile, and was compared to the COPERT one.

The CRUISE vehicle models developed were based on BMW X1 sDrive20d Efficient Dynamics (diesel) and the Fiat Punto 1.3 (gasoline) data. Both vehicle models were pre-validated using fuel consumption measurements conducted in the chassis dynamometer facility of the Laboratory of Applied Thermodynamics, using real-world measured road load settings. Validation results for the BMW X1 model are given in Table 1. It is evident that there is a good agreement between simulated data and measurements – less than 3% difference in all cases. Similar results were calculated for the CRUISE model of the Fiat Punto vehicle.

Table 1: Experimental (chassis dyno) and simulated fuel consumption for the BMW X1 sDrive20d Efficient Dynamics; simulation performed with AVL CRUISE.

	FC Experimental [L/100 km]	FC Simulated [L/100 km]	Deviation [%]
UDC	7.3	7.1	-2.7
EUDC	4.9	4.9	0.0
NEDC	5.8	5.7	-1.7

Results

Madrid test case

For both Madrid and Turin data the average speed, mean positive acceleration and stop time of all traffic situations were calculated from the corresponding second by second speed data. The Madrid data were simulated for one section of the (west) "M30" urban ring highway using PTV VISUM software (http://vision-traffic.ptvgroup.com/en-us/products/ptv-visum). This section is shown in Figure 2.

Figure 2: Map of the "M30" Madrid section simulated and schematic representation using PTV VISUM.

Figure 3 shows the effect of different saturation levels on second by second speed profiles in "M30". The instantaneous speed is almost constant when the saturation is low and the trip lasts for only few seconds because of the high average speed. However, when the saturation level increases, the instantaneous speed drops with much more dynamic variations, while the trip lasts much longer due to this lower average speed.

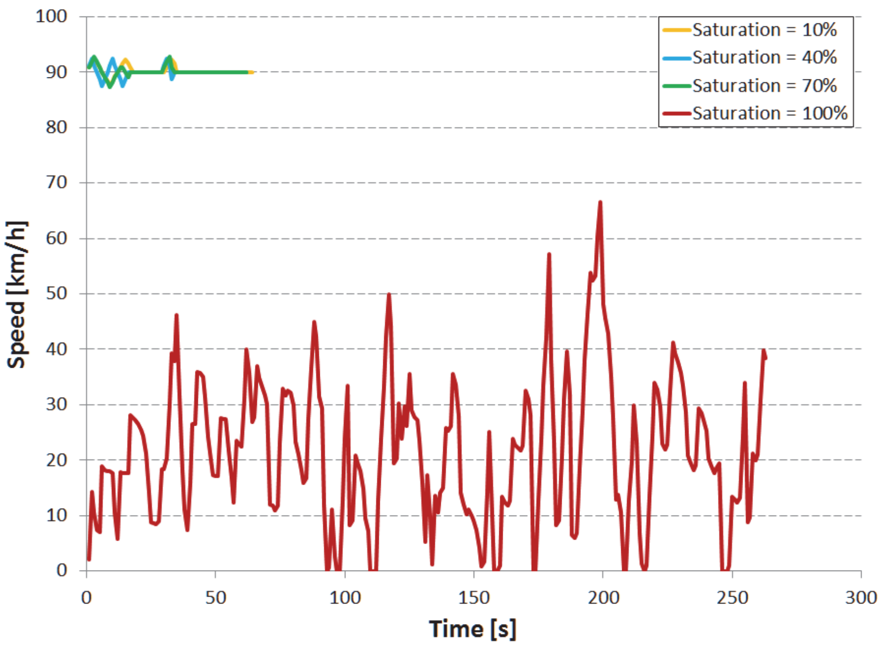

Figure 3: Second by second speed profiles for different saturation levels on a section of the "M30" urban highway.

A summary of traffic indicators as a function of different saturation conditions is shown in Figure 4. When the saturation level starts to exceed 80% the instantaneous speed profile changes dramatically; there are a lot of accelerations and decelerations that cause an increase in stop time and mean positive acceleration, while the average speed decreases as a result of the congested driving conditions.

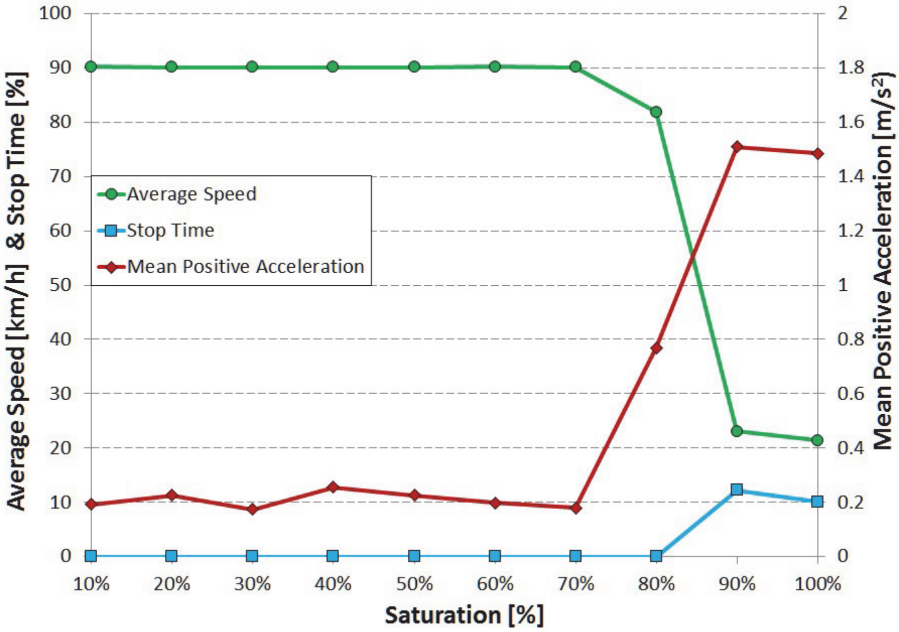

Figure 4: Impact of saturation level on traffic indicators in the Madrid “M30” urban highway.

The effect of different saturation levels on the fuel consumption calculated with COPERT for gasoline 0.8 – 1.4 l Euro 5 vehicle is presented in Figure 5. The results show that up to 80% saturation, the macro emissions model calculates almost constant fuel consumption, as there is no significant change in the average speed. However, at higher saturation levels there is a large increase in the predicted fuel consumption. Still, it remains to be seen whether this increase is realistic or not.

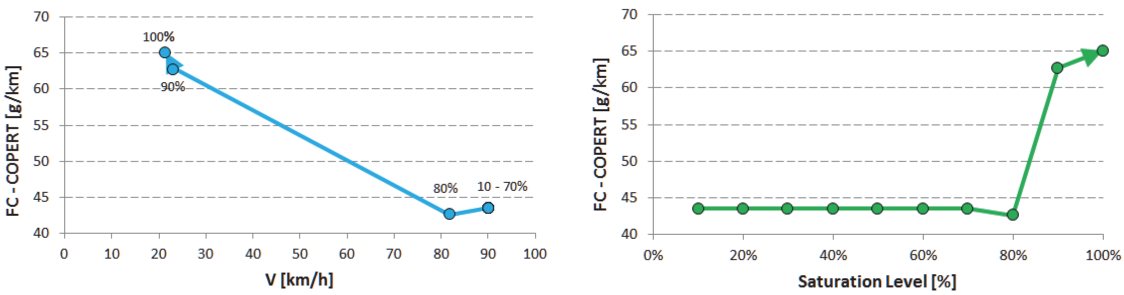

Figure 5: Fuel consumption calculated with COPERT for different saturation levels in the Madrid “M30” urban highway as a function of speed (left) and saturation level (right).

The effect of saturation on fuel consumption is also reflected on the results from the CRUISE Fiat Punto 1.3 gasoline model (Figure 6). In this case, second by second profiles have been used to calculate fuel consumption. When moving from saturation level 10% to 100% both COPERT and CRUISE calculate an increase in fuel consumption, by approximately 50% and 170%, respectively. Up to 80% saturation there is consistency between the two methods. However, beyond 80% saturation COPERT cannot reproduce the effect of increased saturation on the “M30” highway. The difference in the absolute levels between COPERT and CRUISE is to be expected because a generic vehicle category has been used in the case of COPERT and a specific vehicle model – that falls into the corresponding COPERT category – has been used in CRUISE. Hence, the relative trends, rather than the absolute levels are of interest here. When saturation increases above 80%, it is evident that CRUISE calculates much higher fuel consumption than what COPERT does.

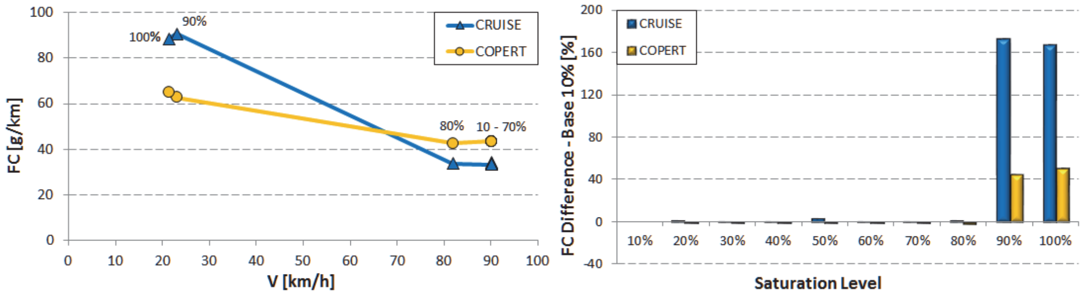

Figure 6: Effect of saturation level on fuel consumption calculated with COPERT and CRUISE (left). Relative fuel consumption using the corresponding values at 10% saturation as reference (right).

Similar behaviour in fuel consumption was observed when the same traffic data used as an input to the corresponding diesel vehicles (COPERT: diesel 1.4 – 2.0 l Euro 5, CRUISE: BMW X1 sDrive20d Efficient Dynamics diesel). Comparing the results of both models in 10% and 100% saturation, COPERT fuel consumption showed a 40% increase, whereas the corresponding CRUISE was 214%.

Turin test case

The results from Madrid traffic data – both for gasoline and diesel vehicle – indicated that after a certain saturation level – in the order of 80% – the average speed fails to adequately express changes in the driving pattern. However, since those calculations were performed using urban highway traffic data, another case study was conducted in order to investigate if such a deviation is present also in more typical urban traffic conditions.

An urban corridor in Turin, “Corso Lecce”, in its part between “Corso Regina” and “Via Lera”, was selected as a case study. This corridor consisted of 6 sections and 5 junctions and was simulated using the AIMSUN model (http://www.aimsun.com/wp). A map and a graphical representation of the simulated road in AIMSUN are shown in Figure 7. Only vehicles entering from the southmost entrance and exit from the north end of the corridor were considered in the simulations. Three different time slots of a typical weekday were simulated (5:00 – 6:00, 12:00 – 13:00 and 8:00 – 9:00), corresponding respectively to free, normal, and saturated driving in the particular corridor.

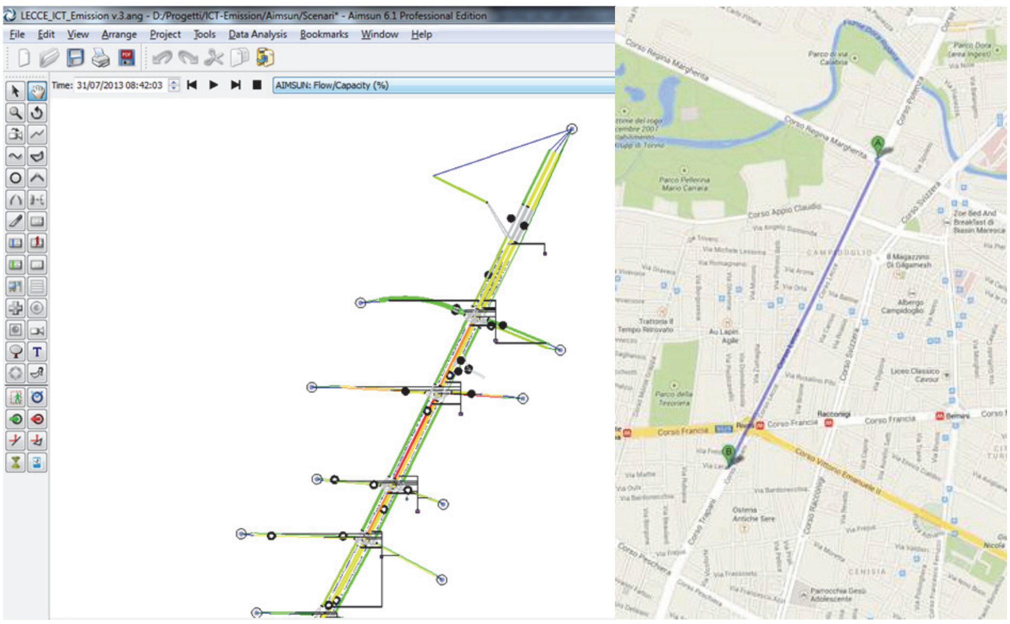

Figure 7: Map of the “Corse Lecce” corridor in Turin and schematic representation using AIMSUN.

The average statistics for each traffic condition are summarized in Table 2. Moving from free to saturated flow the increased vehicle flow – over the same road capacity – causes a reduction in average vehicle speed. As a consequence, and similar to the Madrid case, there is a substantial increase in travel time, number of stops and stop time with increasing saturation.

Table 2: Average traffic characteristics from an urban road in Turin simulated with AIMSUN.

Traffic Condition	Free Flow	Normal Flow	Saturated Flow
Hour Of The Day	5:00 - 6:00	12:00 - 13:00	8:00 - 9:00
Average Speed [km/h]	39.0	27.7	23.2
Travel Time [sec]	152	214	256
Flow [veh/h]	15	453	780
Number Of Stops [-]	2.7	4.4	5.1
Stop Time [sec]	48	98	132

Since the time required to micro-simulate with CRUISE all the vehicles in the corridor for every hour would be enormous, it was decided to only use some representative vehicles. Thus, using the simulated data from AIMSUN, one random vehicle was selected for every traffic condition (free, normal, and saturated). For each of the 6 sections of the simulated road, the average speed, mean saturation and fuel consumption were calculated both with COPERT (diesel 1.4 – 2.0 l Euro 5) and CRUISE (BMW X1 diesel).

The same calculations were repeated for all vehicles, but by increasing the number of sections considered in order to examine the impact of road length on the results. Therefore, a composite of section one and two, was considered, then sections one, two and three, and moving along until finally the complete corridor, consisting of the six sections was simulated. The calculated fuel consumption values retrieved from both COPERT (diesel 1.4 – 2.0 l Euro 5) and CRUISE (BMW X1 diesel) were compared using absolute and relative differences.

The average speed and saturation levels for the 6 individual sections are presented in Figure 8. In general, the saturation for each road section varies from 3% up to 87%. The highest saturation value, almost 90%, occurred in the 3rd section (probably the only congested section among the six). In all sections the effect of saturation is accompanied by a reduction in the average speed of the vehicles. This effect is more evident in sections 4 and 5.

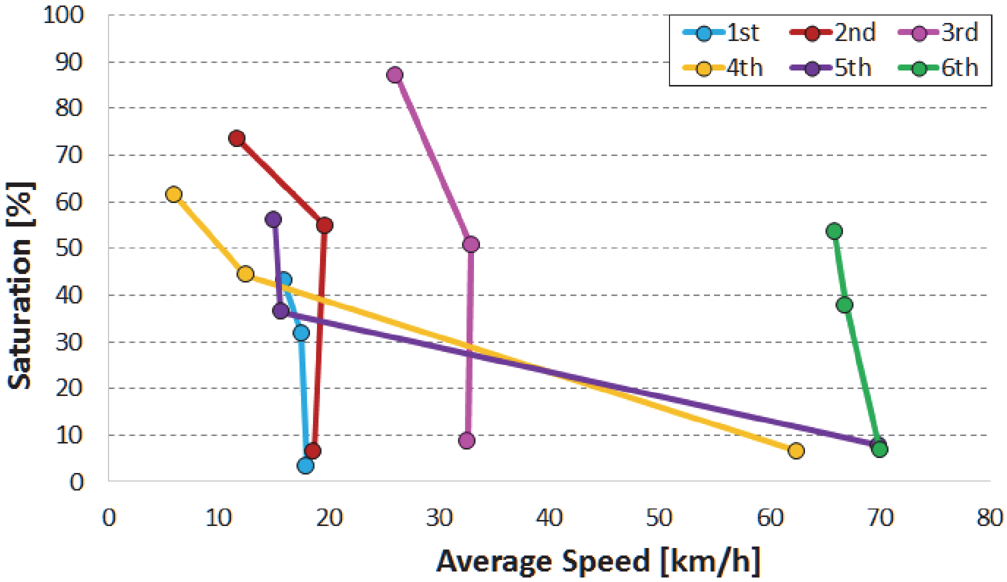

Figure 8: Average speed vs. saturation of the 6 sections of the simulated urban road in Turin based on the selected three vehicles.

In order to calculate the average fuel consumption with COPERT, 18 average vehicle speeds (3 vehicles x 6 road sections) were used. Similarly, each of the 18 different speed profiles was inserted in CRUISE and the corresponding instantaneous fuel consumption was calculated. In order to express results as a function of distance, calculations over each segment were integrated to the ones of the previous segments. The fuel consumption calculated by both COPERT and CRUISE are shown in Figure 9. It is apparent that CRUISE calculates higher fuel consumption but the trends between COPERT and CRUISE are similar.

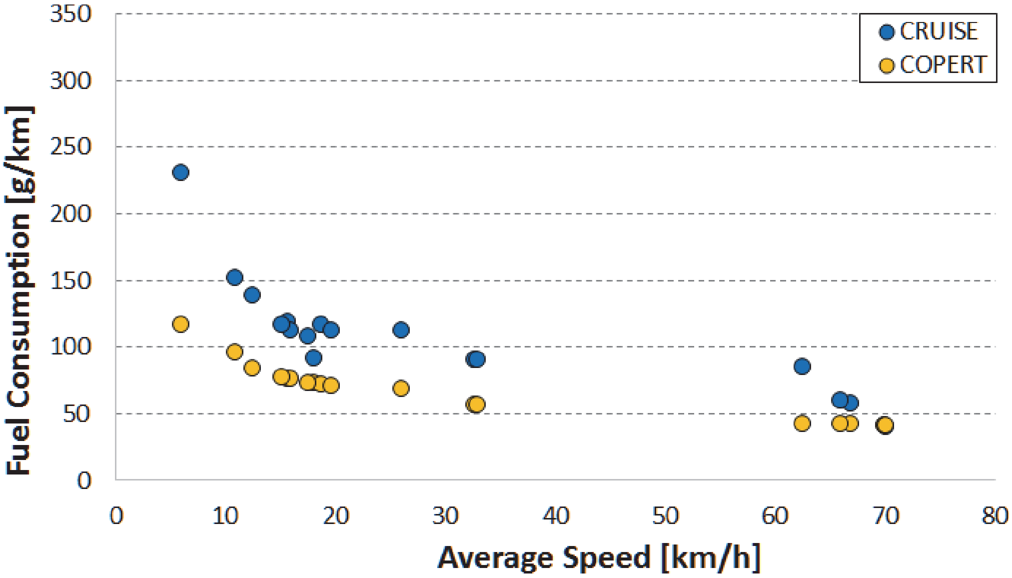

Figure 9 Fuel consumption calculated with both CRUISE and COPERT based on driving profiles of the selected three vehicles.

Similar to Madrid case, the relative fuel consumption differences for each speed rather than the difference in the absolute levels between COPERT and CRUISE are of interest in this comparison. The relative impact of the driving condition on fuel consumption is shown in Figure 10. In this chart, the “normal” case has been taken as a reference for each road section and the relative impacts of the free and congested conditions over this reference were calculated with COPERT and CRUISE.

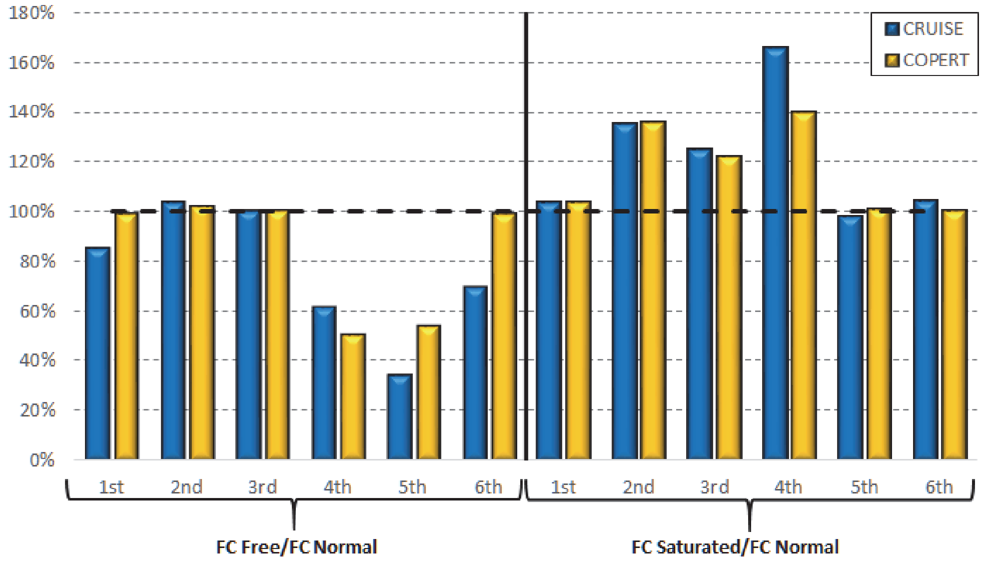

Figure 10: Relative fuel consumption differences calculated with both CRUISE and COPERT based on driving profiles of the selected three vehicles. The calculated fuel consumption values in normal traffic conditions were used as the 100% basis in both models.

Results in Figure 10 indicate that the relative fuel consumption differences calculated with both models are qualitatively similar. In other words, COPERT seems to satisfactorily predict the trends in the impact of saturation even within an urban network. On a quantitative level, individual differences between the two models are present in several cases. In general, the sensitivity of CRUISE to changes in the road conditions are larger than what COPERT predicts. This is also expected, as macro scale modelling tries to simulate fleet level effects and no effects on single vehicles.

The impact of road length is examined in Figure 11, where the saturation level and average vehicle speed are calculated over the 6 road sections, by gradually increasing the road length (1st section only, 1st and 2nd section, up until the entire road is completed – 1st to 6th section). In general, as the road length increases the average vehicle speed increases too (the 1st to 6th section curve is on the rightmost side of the chart), while saturation level does not change substantially between similar traffic conditions. A comparison between the traffic characteristics of the first link and the entire road section (links 1 to 6) shows that in the latter case a change in saturation causes a significant change in average speed.

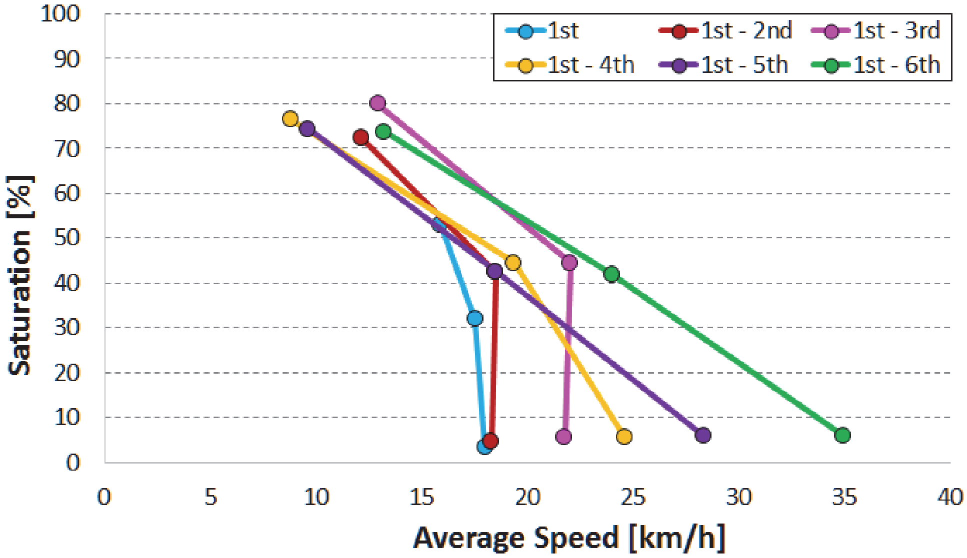

Figure 11: Average speed vs. saturation of the simulated urban road in Turin based on the selected three vehicles; impact of road length.

A longer road section seems to smooth out the differences between relative fuel consumption calculated with both COPERT and CRUISE. The chart in Figure 12 implies that as the road length increases there is a shift from micro towards the macro level in terms of driving profile and fuel consumption. A longer driving profile (i.e. 1st to 6th – corresponding to the entire simulated road) will have much more "average" characteristics than a shorter one (i.e. 1st section only). In this way, the average speed of a vehicle circulating in a large road would be more representative and closer to COPERT average speed, while in short roads the average vehicle speed is probably not representative of the driving profile.

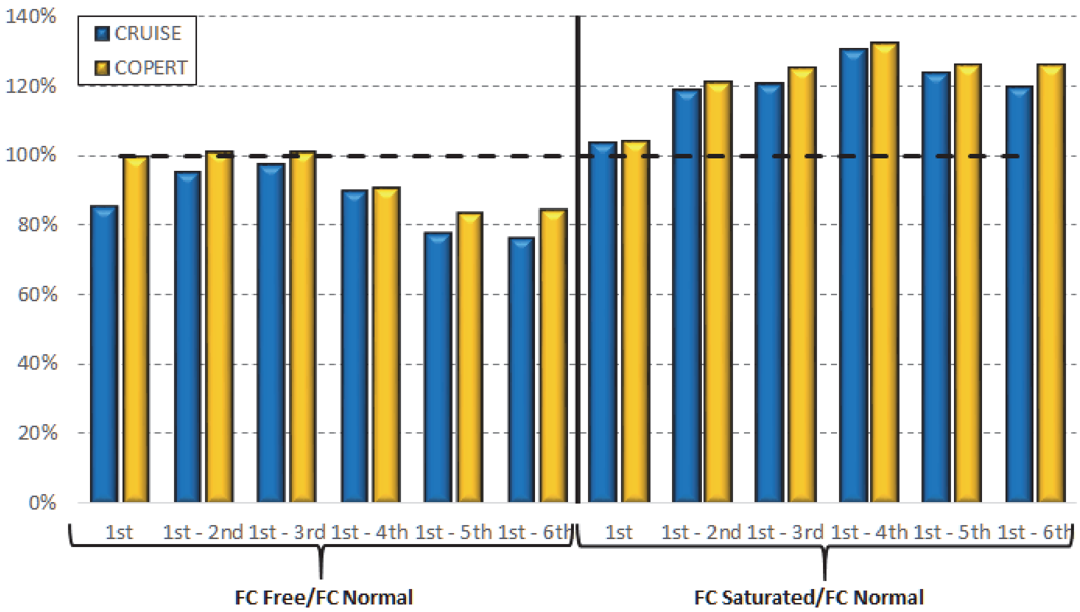

Figure 12: Relative fuel consumption differences calculated with both CRUISE and COPERT according to driving conditions and cumulative number of segments. The calculated fuel consumption in normal traffic conditions was used as basis in both models.

In Figure 12 the values of relative fuel consumption calculated with COPERT are always above the corresponding CRUISE values on the free over normal part of the chart. This indicates that the absolute fuel consumption values on free flow conditions are higher than the corresponding values calculated with CRUISE. In free flow conditions the vehicle activity is low, hence, by definition it is not a frequent condition, while its contribution to the total fuel consumption is small. If an urban network is in free flow conditions, there is little you can do to substantially improve fuel consumption. Moreover, such differences on the exact absolute levels should be seen in the light of the fact that the CRUISE simulations have been conducted on a single vehicle only. Other vehicles with different efficiency characteristics might result into a different performance. Hence, general trends need to be only revealed in this comparison.

In order to examine the combined effect of saturation and road length, the previous results – for the increased road section – were plotted on Figure 13. The x and y axes on this chart represent the road length and the saturation level respectively. The maximum road length in this chart is 1572 m, which corresponds to the sum of length for links 1 to 6, whereas the minimum is 217 m (length of the 1st link only). On z axis there is the ratio:

$$(\text{FC CRUISE} / \text{FC CRUISE}_{\text{normal}}) / (\text{FC COPERT}/ \text{FC COPERT}_{\text{normal}}).$$

This compares the internal relative differences in the consumption calculated by the two models as either the length or the level of congestion vary. When this ratio is equal to one, both COPERT and CRUISE calculate the same relative fuel consumption difference when either the distance, or the level of saturation change. Consequently, in the areas where the ratio is equal to one – or close to one, it is considered "safe" to use COPERT for calculating fuel consumption (assuming that the CRUISE driving-pattern calculated fuel consumption is the correct one).

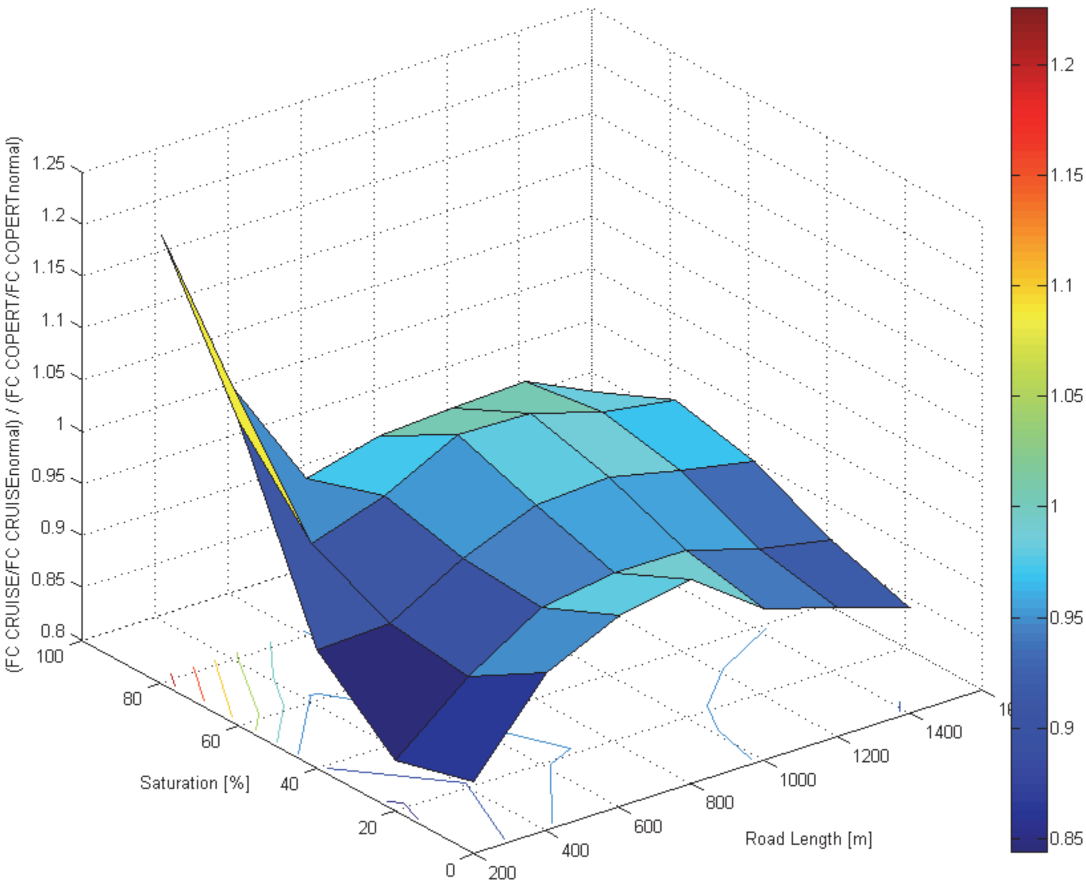

Figure 13: Impact of saturation and road length on the ratio of relative fuel consumption calculated with both CRUISE and COPERT.

This shows that the COPERT relative differences are similar to CRUISE over a large area of the graph but the trends change when simulated distance drops and, in particular, when saturation increases.

Discussion and Conclusions

The results from case studies revealed the application range and the limitations of using the average vehicle speed as the only traffic parameter to estimate fuel consumption using macro emissions models, such as COPERT. The analysis was conducted on the basis of measured and simulated data in an urban corridor and in simulated data on an urban highway.

In most of the traffic situations studied, the fuel consumption calculated using the average speed satisfactorily predicted both the trend and the magnitude of the change, compared to a baseline condition. There were of course individual differences between the fuel consumption derived by using the exact driving profile in CRUISE and the one calculated by COPERT on the basis of the average speed. However, these differences are sporadic and rather random in nature and they do not seem to introduce any particular bias. The simulation using the average speed alone can be considered safe in these cases. The CRUISE simulations were conducted on single vehicles only, hence individual differences with COPERT may also depend on vehicle particularities, as the COPERT functions refer to a fleet of vehicles and not to single vehicles only. Using a different vehicle model or the same vehicle over a different driving pattern with the same average speed might produce an absolute levels difference, which is in the opposite direction than we currently observed. These findings further confirm the largely accepted practice that the average speed based emission factor is a satisfactory approach in estimating emissions at a macro level.

There were two characteristic cases though where the macro emission model based on average speed failed to satisfactorily predict emissions. The first had to do with predicting emissions in very short urban links, i.e. those with a length of less than 400 m. In this case, average speed was not proven to be a very good determinant of emissions and consumption. This is to be expected since, by definition, very short links cannot be modelled at a macro level. For such short distances, the stylized driving pattern cannot be correctly represented by an average speed model. The results collected therefore show that COPERT maximum resolution is down to approximately 400 m, for an urban network. If shorter distances need to be modelled at a macro level, then it would be safer to aggregate short links to larger conglomerates.

The second characteristic case where average speed failed as a determinant of emissions and consumption was for congestion levels higher than approximately 80%. The results of the simulation in the Madrid highway showed that when saturation exceeded this threshold the mean speed dropped by more than 4 times (down to 20 km/h) and the mean positive acceleration became 8 times higher. Basically, driving becomes a constant step and go event with little idling and harsh accelerations to keep up with the jerky traffic. This is different than urban driving with the same average speed. Hence, COPERT emission factors, which are based on urban conditions, for a speed of 20 km/h tend to underestimate the impact of saturation on CO_2 emissions and fuel consumption. For the Turin case, the impact of saturation was not as clear. This might also have been an effect of the selection of the particular urban corridor. Due to its layout, high congestion in this corridor appears only on a single segment (segment 3) which acts as a bottleneck for the subsequent segments. Hence, we could not observe saturation levels above 80% for the complete corridor in order to come up to reliable conclusions. However, at this stage we have to recommend that COPERT macro should not be used in congested networks where saturation exceeds 80%. If this has to be conducted, then the following recommendations are given:

1. COPERT should be expected to underestimate emissions and consumption at high congestion levels. Hence, if a measure is introduced that decreases congestion, then the actual (positive) impact on emissions and consumption will be higher than what COPERT estimates.

2. If high congestion occurs only in specific short segments (<400 m) then it is safe to aggregate these with neighbouring segments. This would lead to an overall uncongested case and a speed which can be a reliable input to COPERT.

3. If congestion occurs on a relatively wide part of the network, then the recommendation would be that a model with micro-scale capabilities to be used in order to predict fuel consumption effects.

As a final conclusion it should be stated that all these results have been performed on the basis of fuel consumption predictions only. It might be expected that different conclusions would be reached if the simulations were repeated for a pollutant rather than fuel consumption. However, in that case the analysis would be much more difficult to execute because individual vehicles may exhibit unique pollutant behaviours with speed and driving pattern, depending on the calibration of their emission control system.

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