Ex-post environmental and traffic assessment of a speed reduction strategy in Madrid’s inner ring-road

Fiamma Perez-Prada , Andres Monzon

Abstract

Since urban traffic is a major source of CO\textsubscript{2} and NO\textsubscript{x} emissions, cities play a key role averting climate change and combating air pollution. Most researchers agree on the need of designing comprehensive mitigation strategies instead of applying isolated measures. Nevertheless, it is important to understand the specific impact and scope of each measure to look for the most effective synergies among them. In 2004, the Madrid City Council launched a plan to re-design its inner ring-road to move traffic out of the city centre. For safety reasons the planned speed limit for the full-renovated South-West section was finally reduced from 90 km/h to 70 km/h. Besides contributing to traffic safety, this strategy could also be seen as positive to the environment due to the associated reduced fuel consumption and lower emissions. However, lower speed limits have lower rates of community acceptance due to its impact on average travel times at the individual level. This paper conducts an ex-post evaluation of this speed reduction strategy to explore its environmental and traffic performance impacts. The results support the thesis that, in this velocity range, lower speed limits present important opportunities for reducing GHG and air pollution in the section affected by the measure, without substantially altering traffic performance. The implementation of the new speed limit policy produces a 14.4% and 16.4% reduction in CO\textsubscript{2} and NO\textsubscript{x} emissions respectively, while global travel time remains virtually constant and the saturation rate decreases slightly. Besides, this cost-effective measure reveals great potential to reduce air pollution in highly populated urban areas located next to urban highways. This work provides local policy makers and city managers with useful insights regarding potential co-benefits of traffic optimization and speed reduction management to reduce mobile source emissions in urban environments.

1. Introduction

In the EU-27, transportation is responsible for 20.3% of total greenhouse gas emissions, and about 88.2% of all GHG emissions are related to CO\textsubscript{2} (EEA, 2012a). The transport sector is also a key source of air pollutant emissions, and accounts for 58% of emissions of NO\textsubscript{x}, 18% of NMVOC, 30% of CO, 21% of SO\textsubscript{x}, 27% of PM\textsubscript{2.5}, and 22% of PM\textsubscript{10} (EEA, 2012b). At an urban level, it is estimated that cities account for two-thirds of the world’s overall energy consumption and contribute an estimated 70% of the world’s GHG (IEA, 2014). Particularly, urban transport contribution to CO\textsubscript{2} emissions is estimated at around 25%. Moreover, road transport is the largest contributor to NO\textsubscript{x} emissions in urban environments (EEA, 2006). The average contribution of urban and local traffic to NO\textsubscript{x}, which is one of the components of NO\textsubscript{x} concentration, is estimated at 64% (Sundvor et al., 2012). Furthermore, an increase in transport activity, and hence a rise in transport emissions, is expected in the near future due to: (i) the predicted growth in urban population (over half the world population now lives in cities, and estimates indicate that over 70% will do so by 2050), (ii) the predicted growth in passenger vehicles (there are about 1.2 billion passenger vehicles today, a figure that is expected to reach 2.5 billion by 2050 (UN-HABITAT, 2011), and (iii) the current trend of urban decentralization in virtually all metropolitan areas (Giuliano and Small, 1999).

A number of authors are examining the role of transportation in climate change mitigation, both in general (e.g. Schipper and Fulton, 2003; Wright and Fulton, 2005; Åkerman and Höjer, 2006; Chapman, 2007; Bristow et al., 2008; Yang et al., 2009) and at an urban level (e.g. McAndrews et al., 2010; Banister, 2011a; Hickman et al., 2013). All of them suggest that there is not a single measure to effectively reduce GHGs; therefore, mitigation strategies should be designed with a comprehensive approach. Successful solutions to achieve low-carbon transport systems should include, but are not limited to, land-use interventions, promotion of public transport systems and non-motorized transport modes, improvement of vehicle fuel efficiency and implementation of transport demand management strategies and traffic management solutions.
Although most researchers agree on the need to design holistic transport emissions reduction policies instead of individual measures, it is critical to understand the explicit impact and scope of each isolated measure in order to (i) better understand potential co-benefits, (ii) look for the most effective synergies, and (iii) select the most appropriate geographic area to apply them. This paper shows how implementing a cost-efficient measure in one artery of the city it achieve to emissions reduction and operation benefits for the whole city is possible. To do so, it conducts an ex-post evaluation of a speed reduction strategy in Madrid’s inner ring-road (M30) using a model for the joint assessment of the impact of reduced speed limits on traffic operation and emissions in the city of Madrid (Spain). In particular, this paper will analyse the effects of reducing the speed limit from 90 to 70 km/h on an 8.8 km section of the M30.

This work provides local policy makers and city managers with useful insights regarding potential co-benefits of traffic optimization and speed reduction management in order to reduce mobile-source emissions in urban environments. In contrast to previous studies, this paper takes both the environmental and traffic performance impacts of the measure into account, as well as the different spatial effects of GHGs and air pollutants.

The following section explains the importance of traffic and speed management strategies in fighting both climate change and air pollution. It compiles different examples of CO2 and NOX reduction strategies, highlighting the fact that usually scant attention has been paid to the joint impact on emissions and traffic performance. Section 3 provides background information on the city of Madrid, and specifically on the M30 ring-road where the speed limit reduction was applied. Section 4 explains the assessment model, scenarios and indicators used for the joint analysis of traffic performance and emissions. Section 5 reports the results of the assessment model in terms of the variation in the selected traffic performance and emissions indicators for an average working day. Finally, the assessment conclusions and policy recommendations are set forth in Section 6.

2. Literature review

From a macroscopic point of view, transport emissions are a function of driving conditions (average speed is the input for macroscopic emission models, although traffic dynamics are also important), total travel activity (km travelled), and vehicle technology and fuel efficiency. Traffic management strategies can affect the first two factors, which are indeed closely related. Among all traffic management strategies, one of the most cost-effective ways of reducing road transport emissions is lowering speed limits (TRB, 2012). A recent study on Spanish motorways (Monzon et al., 2012) concludes that, out of those analysed, the most effective traffic management strategy to reduce emissions is the reduction of motorway speeds for cars, finding also borne out by the sensitivity analysis.

Higher speed transportation fosters economic development by enhancing mobility, decreasing travel times and facilitating access to goods, services and facilities. Higher speeds still enjoy significant rates of support from society and industry, although they imply major adverse impacts on safety, environment and the liveability of urban areas (ECMT, 2004). Speed limits have traditionally had a twofold function (Archer et al., 2008). On the one hand, they limit maximum speed to improve safety, and on the other, they reduce dispersion in driving speeds, which not only increases safety but also improves traffic efficiency. Like Sweden Vision Zero (Tingvall and Haworth, 1999), numerous other studies support the idea that lower speed limits lead to a significant reduction in traffic accidents (Woolley, 2005; Aarts and Van Schagen, 2006; De Pauw et al., 2013).

New trends arising from global concern about climate change also ascribe an energy conservation function to speed limits. It is well known that during the 1970s oil crises, the US government applied a nationwide speed limit reduction of 90 km/h to conserve fuel, which remained in effect for almost 25 years. In several countries in Europe, as well in Spain, this measure was replicated by setting a range of speed limits. In 2011, for energy conservation reasons, the Spanish government lowered the motorway speed limit again, in this case from 120 km/h to 110 km/h. Asensio et al. (2014) evaluated this policy and found evidence of a 2% to 3% fuel consumption reduction. Although lower and more strictly-enforced speed limits have proved to be a straightforward and efficient policy for reducing road transport externalities (accidents, emissions, noise and so on), community acceptance is still low due to its impact on average travel times at the individual level. However, the effects of speed on reducing travel times tend to be overestimated, especially in urban areas where time savings are often small or negligible due to short trip length and frequent stop-and-go cycles, usually caused by numerous intersections, traffic lights or heavy congestion rates (Archer et al., 2008). Moreover, current trends in transport sustainability research suggest that both distances travelled and speed should be reduced to look for positive co-benefits for the environment, energy, social inclusion, wellbeing and the economy (Banister, 2011b). This proposition is also supported by May et al. (2011), who argue for the integration of sustainable transport and road safety policies to facilitate better environmental and road safety outcomes. According to the results of a European public poll (FER, 2011) about two thirds of EU citizens were willing to modify a car’s speed in order to reduce emissions. However, about 40–50% of drivers (up to 80% depending on the country and type of road) drive above the legal speed limit.

A number of studies have examined the relationship between speed limits and reduced emissions or fuel consumption. In Germany, a 4.8% reduction in fuel consumption was achieved after lowering the speed limit to 100 km/h on motorways and 80 km/h on roads outside urban areas (GIER, 1996). A recent study on Spanish motorways (Monzon et al., 2012) concludes that the reduction of motorway speeds for cars, compared to a 5.5% reduction in CO2 emissions. Most studies also show that a reduction in speed limits leads to lower air pollutant emissions. In Austria, lowering speed limits on motorways from 130 km/h to 100 km/h led to a 17% reduction in NOx, and 25% in CO2 emissions (ECMT, 1996). Keuten et al., 2010 conducted a study in Rotterdam showing a 5–30% decrease in NOx emissions after reducing the speed limit from 100 km/h to 80 km/h on its urban ring-road. Orbital motorways bring about major environmental problems: barrier effects, noise, air pollution and GHG emissions due to their high annual average daily traffic (AADT), high average speeds during off-peak hours, and high congestion rates during peak hours. There are a number of studies assessing their impact on transport, accessibility and land use (e.g. Gutiérrez and Gómez, 1999); however, there are scant examples analysing their environmental impacts (Monzon et al., 2005) and even fewer of how implementing lower speed limits in orbital motorways can reduce traffic emissions (Keuten et al., 2010). Environmental issues are crucial in cities where urban ring-roads run through dense built-up areas, which is the case of M30 (Monzon and Villanueva, 1996).

Some of the studies mentioned before introduce some examples of how lower speed limits can reduce traffic emissions. However, there is a lack of studies and tools combining the two points of view: traffic analysis and exhaust emissions. Besides, the impact lowering speed limits has on travel times remains questionable (Shehe and Rietvet, 1997) and, according to the European Environmental Agency (EEA, 2011), it could be more acceptable through scientific evidence and knowledge-sharing. The joint assessment proposed in this paper will provide insights on the environmental benefits of speed reduction policies, as well as on their potential trade-offs regarding urban mobility.

3. Case study background and relevant targets

Madrid is a city of 3.5 million inhabitants, and 6 million in its metropolitan area. It is undergoing a rapid suburbanisation process, in which population and jobs are moving out of the city centre. This process is
leading to longer trips and greater car dependency. As a result, the city of Madrid consistently fails to meet the air pollutant limits set by European legislation: NO2 levels have exceeded the 200 mg/m³ limit an average of 23 times during 2015 (Madrid, 2015). Transport in the city of Madrid accounts for 47.3% of total CO2 emissions and 82% of NOx emissions, of which 85% and 83%, respectively, come from road transport (Madrid, 2011). A wide variety of strategies have been considered to reduce both types of emissions, which included promoting the use of less polluting cars and fuels, public transportation and walking and cycling, the implementation of parking restrictions, the pedestrianization of historic zones, and the restriction of private vehicles in the city centre (Madrid, 2011).

In addition, in 2004, the Madrid City Council launched a plan to redesign the 32 km inner ring-road, M30. It acts as a boundary between the Central Business District (CBD) and the rest of the city, and structured the traffic from the periphery towards the CBD (see Fig. 1). Besides improvement in road safety, the main goals of this renovation were to reduce environmental pressure and the pedestrian barrier effect. As a whole, M30 contributes to 9.4% of the metropolitan area’s daily traffic and 24.2% of Madrid’s. At the same time, its contribution to CO2 emissions is 8.2% for Metropolitan Area and 21.9% for Madrid. Finally, it contributes 8.6% to NOx emissions of metropolitan area and 23.1% of Madrid.

Due to the traffic distribution function, the M30 has an important potential for reducing urban transport emissions, and especially air pollutants in the highly-populated surrounding area. In fact, the new Protocol for High Nitrogen Dioxide Pollution Levels (Madrid, 2016), force a 70 km/h speed reduction in M30 and some arterial roads after one day of NO2 concentration levels over 180 mg/m² in two measurement stations of the same area. The protocol, approved in 2016, consider four scenarios of pollution concentration levels. These scenarios added new traffic restriction measures as the level of alert increases. The traffic restriction measures range from speed reduction to banning traffic in the city centre.

3.1. The M30 ring-road: past and present

The M30 had a heterogeneous design through consolidated built-up areas, and ran very close to the city centre – < 1.5 km in the west section – consequently causing substantial problems with noise, air pollution and accidents. In broad terms, renovation consisted of a more uniform layout and better integration with urban arteries, intended to improve the level of service, reduce congestion rates and diminish accidents. It included the construction of 12 km of tunnels in the South-West section and, in the East section, the improvement of the transfers between side and central lanes, eliminating all the left side exits, as well as the revaluation of all the links in this section. This project was supported by a socioeconomic study to assess the environmental and operational benefits of the remodelled layout. Savings in time and CO2 emissions accounted for 75% of the socioeconomic benefits of the programme. After three years of construction work, the new M30 was fully operative in 2007.

Nowadays, M30 is a continuous 3 + 3-lane urban motorway, except for about 1.5 km in the northern section where it becomes an urban boulevard. Its AADT varies widely throughout its three sections, but is about 200,000 vehicles on average. For the purpose of this analysis, the M30 has been divided into three main sections, according to their degree of restoration, different speed limits and traffic volumes (cfr. Table 1 and Fig. 1). Each section was also divided into smaller subsections. This study excludes service roads and branch lines. Driving length refers to the actual length a person travels when driving in one direction. Network capacity is the aggregated capacity of each section and subsection, and represents the maximum traffic intensity it can carry per hour.

- **South-West (SW) section**: This section was completely rebuilt. The South and South-West of M30 is a highly populated area located very close to the city centre and to the city’s main river. It was buried to reduce the environmental pressure and congestion problems also to recover the livability on the river banks eliminating the barrier effect of the former road. The planned speed limit for the tunnel sections was 90 km/h – the same speed as for open air sections; however for safety reasons the speed limit was finally set at 70 km/h.

- **East (E) section**: This section was renewed. The enhancement plan of the East section of the M30 ring-road comprised the improvement of the transfers between side and central lanes eliminating all the left side exits as well as the renovation of all the links of this section.

### Table 1

<table>
<thead>
<tr>
<th>M30 traffic features</th>
<th>DL</th>
<th>SL</th>
<th>NC</th>
<th>AADT</th>
</tr>
</thead>
<tbody>
<tr>
<td>La Paloma</td>
<td>0.57</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Costa Rica</td>
<td>2.88</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avda. America</td>
<td>4.02</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O'Donnell</td>
<td>3.15</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mediterraneo</td>
<td>2.54</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>East</td>
<td>13.17</td>
<td>6300</td>
<td>270,000</td>
<td></td>
</tr>
<tr>
<td>Bypass</td>
<td>4.00</td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pte. Toledo</td>
<td>3.10</td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pte. Rey</td>
<td>2.30</td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>South-West</td>
<td>8.80</td>
<td>6800</td>
<td>110,000</td>
<td></td>
</tr>
<tr>
<td>El Pardo</td>
<td>3.59</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>2.95</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ilustracion</td>
<td>1.68</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Link</td>
<td>2.40</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North-West</td>
<td>10.62</td>
<td>6000</td>
<td>95,000</td>
<td></td>
</tr>
<tr>
<td>Total M30</td>
<td>32.59</td>
<td>6350</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- DL (driving length in km).
- SL (speed limit in km/h).
- NC (network capacity in vehicles/h).
- AADT (annual average daily traffic in vehicles).
• **North-West (NW) section**: This section is about did not change. It comprises four subsections; the closest to the tunnel entrance is El Pardo.

4. **Impact assessment methodology**

The aim of this paper is to assess the effects on the environment and on traffic performance of the speed limit reduction in the SW section, using a traffic model and an emissions model (see Fig. 2). The outputs of the traffic model feed the emissions model with average speeds and traffic volumes. The differences between the two scenarios are analysed in terms of traffic volume (vehicles-km), travel times (vehicles-hour), average speeds (km/h), CO₂ emissions and NOₓ emissions (kg/km). The variations between the scenarios always refer to the base scenario; the changes will thus always reflect the effect of the speed limit reduction from 90 to 70 km/h. Similar methodologies have been used in other research papers to assess traffic emissions although using different aggregation levels (e.g. Sider et al., 2013)

The scenarios considered are:

• S90 (Base) – SW section at 90 km/h

This simulates the Madrid traffic situation in 2010, but with the speed limit on the M30 motorway sections set at 90 km/h (except for the Ilustracion subsection, which is an urban boulevard with traffic lights and a 50 km/h speed limit), including the 8.8 km of South-West tunnel section.

• S70 – SW section at 70 km/h

This simulates the current traffic situation in Madrid in 2010: reduced speed limit in the South-West tunnel section to 70 km/h. The speed limit in the rest of the sections of the M30 remains at 90 km/h.

4.1. **Traffic demand model**

A macroscopic traffic model for the year 2010, based on the origin-destination matrices of the Madrid City Council, was used developed. The modelled area comprises the whole of the Madrid region, with a road network of about 6500 km. The effect on traffic from neighbouring regions is negligible compared to the internal traffic of the region. The 2004 Household Mobility Survey was used to calibrate and adjust these OD matrices. This data was updated with traffic information from 2008 and 2009 observed at 491 measurement points around the Madrid Region. Additional (cell, row and column) deviation restrictions were imposed to prevent an uncontrolled distortion between the original OD matrix and the adjusted matrix.

PTV-Visum software was used for transportation modelling. Fig. 3, shows the beltway hourly traffic distribution from 32 measurement points in 2008 and 2009 located along the main and side lanes of M30. Night hours, off-peak hours and peak hours are easily identified. The traffic model was finally developed for three different time periods: morning peak hours (AM from 8 to 10 am), afternoon peak hours (PM from 3 to 5 pm and 6–9 pm) and off-peak hours (OP from 7 to 8 am, 10 am–1 pm, 5–6 pm and 9–11 pm), using the corresponding OD matrix for the average hour in the period. Night hours have not been considered due to their low traffic intensity.

For large urban road networks, traffic models generate macroscopic traffic data for each road link in the network (Smit et al., 2008). The model provides information on length (km), traffic intensity (vehicles/h), capacity (vehicles/h), average speed (km/h) and travel times for each network link.

Changes in the following traffic indicators between S90 and S70 have been used to evaluate the traffic performance of the urban highway.

• VKT (Vehicle Kilometres Travelled): this represents traffic volume as a product of traffic intensity (number of vehicles crossing a specific section in an hour) and section length. It is often described as an indicator

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**Fig. 2. Assessment model flow chart.**
of traffic demand. It characterizes the traffic flow over a road link on an average hour in a day. The model gives three different values of traffic intensity, one for each average hour in the three defined periods: morning peak hour (AM), afternoon peak hour (PM) and off-peak hours (OP). In view of the fact that the test measure in this study – lowering the speed limit from 90 km/h to 70 km/h – changes neither the length or the capacity of the links, both saturation (traffic intensity divided by section capacity) and traffic volume are synonyms of traffic intensity in relative terms.

\[
VKT = \sum_{t} I_{i,p} l_i
\]

where:
- \(I_{i,p}\) is the traffic intensity (vehicles/h) in a specific link of the network for an average hour in the time period considered
- \(l_i\) is the length (km) of the link
- \(i\) represents the links of the network, in this case the links of the model associated to the ring road (M30)
- \(p\) is the time period considered (AM, PM or OP)

- **VEH (vehicles per hour)**: the total travel time of all vehicles on a link or segment of the road for an average hour of the three defined periods. The average daily travel times have been calculated using a similar formulation as for average daily traffic.

\[
VEH = \sum_{t} I_{i,p} t_i p_i
\]

where:
- \(I_{i}\) is the traffic intensity (vehicles/h) on a specific link of the network
- \(t_i\) is the travel time (hours) on a specific link of the network for an average hour in the time period considered
- \(i\) represents the links of the network, in this case the links of the model associated to the ring road (M30)
- \(p\) is the time period considered (AM, PM or OP)

- **AVS (average speed)**: the average speed of the vehicles in a link or a segment of the road for an average hour of the three defined periods. The daily average speed has been calculated using the same formulation as for average daily traffic.

\[
AVS = \frac{\sum_{t} v_{i,p} l_i}{\sum_{t} I_{i,p} l_i}
\]

where:
- \(v_{i,p}\) is the speed (km/h) on a specific link of the network for an average hour in the time period considered
- \(l_i\) is the length (km) of the link
- \(i\) represents the links of the network, in this case the links of the model associated to the M30
- \(p\) is the time period considered (AM, PM or OP)

The daily values of the traffic performance indicators are calculated by multiplying the result for each time period by the length of the period. Both absolute and relative variations between scenarios are analysed.

### 4.2. Emissions model

The "EMEP/EEA Emission Inventory Guidebook 2009" (Ntziahristos and Samaras, 2012) for road transport was used to quantify CO₂ and NOₓ emissions. The selection of the emitters has been motivated by the following reasons. First, both type of emissions are considered in the guidebook, which provides a detailed methodology to obtain them based on specific emission factors and covering different traffic situations (i.e. urban, rural, highway) and engine conditions. Second, CO₂ is the largest anthropogenic emission among the GHGs. Finally, quantifying the amount of NOₓ emitted into the atmosphere is essential for reliable prediction of air pollutants (Tonga et al., 2015), since NOₓ are key precursors to tropospheric ambient ozone (O₃) and fine particulate matter (PM₂.₅) (Crutzen and Gidel, 1983 and Spicer, 1983). On the other hand, the term NOₓ includes NO and NO₂ emissions and the emission inventory guidebook considers NO₂ as an equivalent term for NOₓ. Previous studies have concluded that traffic-related pollutants are characterized well by
NO₂ (Beckerman et al., 2008), which is therefore used as a common marker for traffic-related air pollution (Han and Naeher, 2006).

The guide specifies different types of analysis depending on the data available. Traffic models are commonly used to generate the required traffic data input to emission models (Smitt et al., 2008). The Tier3 methodology was used, since in a macroscopic traffic model such as this, both traffic volume (vehicles-km) and average speed (km/h) are available. To apply the Tier3 methodology, Madrid's fleet per category (see Appendix 1) was classified according to fuel and engine type, and the associated emissions reduction technology. As explained before, the results of the macroscopic traffic model feed the emissions model. Traffic flows and average speed are the main inputs for the model, which implicitly takes congestion rates into account. Since GHG and air pollutant emissions are assessed for an urban highway, cold-start emissions were not taken into account in this evaluation. The basic formula for estimating hot emissions (in grams) for a given time period in the case study was:

\[ Emission = \sum_{i} EF(v)_{m,i,p,k} l_{p,k} \]

where

- \( EF(v) \) represents the emission factor (g/km) provided by the EMEP/EEA Emission Inventory Guidebook 2009 which is directly related to the speed in the link and to the fleet composition
- \( m \) represents vehicle classes (fleet composition) depending on technologies vehicle fuel, engine type and technology
- \( k \) is the type of emission considered, in this case CO₂ and NOₓ

![Daily traffic volumes](image_url)

**Fig. 4.** Daily traffic volumes by section and subsection.
\( \ell \) is the traffic intensity (vehicles/h) in a specific link of the network for an average hour of the time period considered.

\( L \) is the length (km) of the link.

\( f \) is the links of the network, in this case the links of the model associated to the ring road (M30).

\( p \) is the time period considered (AM, PM or OP).

For each emission type, \( k (\text{CO}_2 \text{ and } \text{NO}_x) \), the methodology provides different consumption factors based on two or three speed ranges by vehicle category. Therefore, emissions are computed taking into account average speeds and traffic volumes per link (outputs from the traffic model), Madrid fleet composition and EMEP/EEA emissions factors (external inputs to the emissions model). Finally, the daily values of the emissions indicators are calculated by multiplying the result for each time period by the length of the period. Both absolute and relative variations between scenarios are analysed.

5. Results

This section delivers the results of the scenario modelling for an average working day, and then the daily variations in the traffic performance and emissions indicators by period (AM, PM and OP).

5.1. Average daily results

Daily results are presented in a homogeneous manner for traffic volumes, average speeds, aggregated travel times and vehicle emissions.
The effect of the speed limit reduction is calculated by section and subsection. While the analysis of the sections offers a comprehensive picture of the situation along the road as a whole, the analysis of the smaller subsections explains the impacts of the measure in transition segments; i.e. the subsections closer to the section where the speed reduction measure was implemented. Values are presented in absolute and relative terms, which is particularly relevant in the results for CO₂ emissions due to their global impact; a 1% reduction in CO₂ emissions in one section with high emission levels is more important than a 5% reduction in an section with low emission levels in aggregate terms. The number of tons of CO₂ reduced is therefore more important than the relative reduction in a specific section. Finally, the dispersion among the parameters studied is especially important when studying average speeds.

Fig. 4 shows daily traffic volumes by section (table above) and subsection (graph below) for each scenario, and their absolute and relative variation after the implementation of the 70 km/h speed limit along the SW section. As explained in the Impact Assessment Methodology, the variation in traffic volumes and saturation rates for this speed reduction measure is the same.

As expected, the measure generates a major reduction of almost 13% in traffic volume in S-W section. Traffic volume variation in open-air sections (E and NW) is marginal. There is a 3.5% reduction in traffic volume and saturation rates for the whole M30.

Subsections further away from the where the measure was applied – La Paloma and North Link – have a minor increase in traffic volume, and transition subsections (Mediterraneo and El Pardo) indicate a decrease, as shown in the graph.

Fig. 6. Daily travel times by section and subsection.
The SW section is the most homogeneous stretch of the ring road in terms of traffic volume, which is explained by the fact that this road section has fewer exits and entrances. Traffic volume dispersion in this section is even lower after the speed limit reduction. The open-air sections present high levels of traffic volume dispersion both before and after the implementation of the speed measure.

Fig. 5 shows the daily average speed by section and subsection. The results show that a 22.2% reduction in the speed limit in the SW section (from 90 km/h to 70 km/h) leads to a smaller reduction of 17.8% in the daily average speeds in this section. The speed reduction also causes less speed dispersion between the sections. S90 has a maximum average speed variation of over 13.4 km/h between the E and the SW sections; however, S70 has a maximum variation of 5.1 km/h between the SW and the N-West sections. Considering the ring-road as a whole, the 22.2% speed reduction over less than a third of its length leads to a 4.76% reduction in average speeds. This reduction is mainly due to the reduction in average speeds in the SW section, and directly affects individual travel times.

It is worth noting that the subsections closest to the section where the measure was applied (Mediterraneo and El Pardo) undergo a slight increase in average speed due mainly to the effect of the transition from a 70 km/h section to a 90 km/h section. The results are aggregated for both driving directions; the fact that in these segments the total average speed variation is positive means that the ‘measure effect’ is more powerful when emerging from the section than entering.

Fig. 6 shows daily travel times by section and subsection.

Aggregate travel times remain virtually unchanged when considering the M30 as a whole. In the SW Section they increase 3.3%, but this rise is offset by the 3.0% decline in the N Section.

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**Daily CO₂ emissions**

<table>
<thead>
<tr>
<th>M30 Sections</th>
<th>Network length (km)</th>
<th>S90 (ton)</th>
<th>S70 (ton)</th>
<th>Absolute variation (ton)</th>
<th>Relative variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td>27.96</td>
<td>234.6</td>
<td>254.6</td>
<td>-30</td>
<td>-1.3%</td>
</tr>
<tr>
<td>SW (speed reduction)</td>
<td>20.5</td>
<td>231.5</td>
<td>198.1</td>
<td>-33.4</td>
<td>-14.4%</td>
</tr>
<tr>
<td>E</td>
<td>34.66</td>
<td>425.1</td>
<td>425.3</td>
<td>0.2</td>
<td>0.0%</td>
</tr>
<tr>
<td>Total M-30 Ring Road</td>
<td>83.12</td>
<td>894.3</td>
<td>858.0</td>
<td>-36.3</td>
<td>-4.1%</td>
</tr>
</tbody>
</table>

**Daily CO₂ emissions by subsection**

![Bar chart showing CO₂ emissions by subsection](image)

**Fig. 7. Daily CO₂ emissions by section and subsection.**
Subsections results show that the road segments closest to the zone of implementation of the measure undergo a reduction in travel times (O’Donnell: −1.4%; Mediterraneo: −1.8%; El Pardo: −11.2% and North: −0.9%) due to the decrease in traffic volume and speed in these subsections. SW sections show an increase in travel time, which is not matched by all the subsections in the section, i.e. the Pte. Toledo subsection has a slight decrease in travel times as the reduction in average speed (14.1%) is offset by the lower traffic volume (13.6%). This is not the case for the other two subsections of the tunnel section, where the reduction in average speed is too high (over 19%) to be compensated by the fall in traffic volume.

Figs. 7 and 8 show a 16.4% reduction in NO$_x$ emissions and a 14.4% reduction in CO$_2$ emissions in the SW section. The variation in the other sections of the M30 is almost negligible, and therefore the 4.1% and 4.6% reduction in CO$_2$ and NO$_x$ emissions respectively for the whole of the M30 is mainly due to their variation in the tunnel sector.

These figures also show that the subsections closest to the tunnel section undergo a slight reduction in emissions after the implementation of the new speed limit, while the road segments furthest away see an increase in vehicle emissions.

5.2. Daily variation in results

The model also allows us to analyse the variation in the study parameters throughout the day – morning peak period (AM), afternoon peak period (PM) and off-peak period (OP) – which provides a deeper understanding on how this measure performs at different levels of urban congestion. The emission model implicitly account for some
Table 2
Relative hourly variation in traffic performance and emissions indicators after lowering the speed limit in the South-West section from 90 km/h to 70 km/h on the M-30.

| Traffic performance indicators | VKM (%) | AM 0.1 | −10.2 | −1.8 | −3.4
|                               | PM 0.1  | −11.4  | 0.1   | 3    |
|                               | OP −1.7 | −14.1  | 0.5   | 4    |
| VEH (%)                       | AM −2.8 | 7.7    | −3.7  | −1.2 |
|                               | PM −2   | 4.2    | 0.4   | 0.6  |
|                               | OP −3.8 | 1.6    | 1     | −0.1 |
| AVS (%)                       | AM 1.2  | −18.5  | 1.6   | −4.4 |
|                               | PM 0.1  | −17.4  | 0.2   | −4.8 |
|                               | OP 0.9  | −17.8  | 0.6   | −4.8 |
| Emission indicators CO₂ (%)   | AM −0.5 | −12.1  | 2.2   | −4.1 |
|                               | PM −0.6 | −12.6  | 0.2   | 3.3  |
|                               | OP −2   | −16.3  | 0.5   | −4.6 |
| NOₓ (%)                       | AM −0.1 | −14.2  | 1.8   | −4.5 |
|                               | PM −0.3 | −14.6  | 0.2   | −3.8 |
|                               | OP −1.7 | −18.1  | 0.4   | −5.2 |

Reductions in speed limits have been widely used for safety purposes and – less commonly – for fuel conservation purposes. Speed reduction strategies directly affect two of the main emissions factors (Grote et al., 2016): traffic volumes and speeds. On the one hand, traffic volumes decline, since an indirect effect of lowering speed limits is that roads become less attractive to drivers; and on the other, a drop in the average speed leads directly to a lower free-flow speed. Hence, lower speed limits can have an immediate and cost-effective effect on vehicle emissions. However, it is unlikely to be a popular measure owing to the widespread assumption that it can negatively affect traffic performance, and particularly travel times (TRB, 2012).

This study shows that lowering speed limits on an urban motorway can provide significant benefits in terms of reducing CO₂ and NOₓ emissions, without substantially adding to travel times; the measure therefore offers clear environmental benefits with very little impact on traffic performance. The study analyses the effect of lowering the speed limit from 90 km/h to 70 km/h in a section of Madrid’s inner ring-road, M30. The 22.2% speed reduction is evaluated using a combined emissions and transport model. M30 is divided in three sections: NW, E and SW. The results of the study reveal differing impacts along the road layout and for different congestion levels. The SW section – affected by the speed reduction – shows a slight increase in aggregate (3.27%) travel times. The daily average speed reduction (17.8%) in this section is lower than the speed limit reduction (22.2%), and directly affects individual travel times. As expected, the measure produces a significant reduction in traffic volume at almost 13%. As shown by several other studies (Dijkema et al., 2008; Farzaneh et al., 2010), the implementation of the new speed limit policy leads to a reduction in both CO₂ and NOₓ emissions at 14.4% and 16.4%, respectively. NOₓ reductions are higher than CO₂ reductions for our range of speeds, which is explained by the fact that NOₓ emissions are directly linked to engine temperature, and thus increase at high speeds and loads (ECMT, 2004). The highest reductions in vehicle emissions occur during off-peak hours.

The effects in the sections not directly affected by the measure can be considered negligible. The subsections adjacent to the speed limit reduction undergo variations in traffic performance indices and emission rates of the same sign as in the SW section, and show a reduction in traffic volume, average speed and emissions. Aggregated travel times increase, although usually at a considerably lower rate than in the SW section. Finally, the impact of the measure on emissions and traffic performance is less noticeable for the whole M30. It produces an average speed reduction of 4.76% and a 3.56% reduction in traffic volume. Aggregated travel times remain virtually unchanged. CO₂ and NOₓ emissions undergo a 4% and 4.6% decrease. In conclusion, the results of the study show how selected actions in specific sections could produce sufficiently positive results without affecting global mobility.

6. Conclusions

This paper has assessed the joint impact of a speed limit reduction on traffic performance (traffic volumes, travel times and average speeds) and emissions (CO₂ and NOₓ). It has been applied to a congested section of Madrid’s inner ring-road. Furthermore, the research evaluates both direct impacts on the section where the measure was applied, and the spillover effects onto the whole ring-road and connexion sections.

congestion influence; however, average speed used in the model may lead to uncertainties in particular for the modelling of peak-hour emissions as similar average speeds can be reached with different speed patterns in each link (Smit et al., 2008; Toffoletto et al., 2013).

Table 2 shows the hourly variation in the traffic performance and emissions indicators after the implementation of the 70 km/h speed limit in the tunnel sector. In tunnels, the variation in average speed and traffic volume among periods is <10%, except during off-peak hours when traffic volume is considerably lower than in peak hours. However, travel times in the South-West section differ substantially from one period to another. Differences between AM and PM are explained by the cumulative effect of these minor variations in average speed and traffic volume. During the morning period, traffic volume is about 10% greater than during the afternoon, and average speed is about 10% slower; travel times during morning peak hours are therefore longer (7.7%) than in afternoon peak hours (4.2%).

Travel times during off-peak hours in tunnels rise only 1.6%, as although average speed declines by 17.8%, there is also a substantial reduction in traffic volume (14.1%), which offsets the effect of the average speed reduction.

There are two main reasons why daily variations in travel times remain practically unchanged. On the one hand, the rise in the South-West section travel times is offset by the decrease in travel times in the North-West section; and on the other, although travel times increase considerably during peak hours, these only represent 5 of the 15 h considered in the model.

The model shows that the most important CO₂ and NOₓ emission reductions occur during off-peak hours. This was expected, as the lower saturation rates during these periods make it possible to drive at free-flow speeds most of the time. 22.2% lower free flow speeds can be achieved by lowering speed limits to 70 km/h.

The effect of the measure during peak hours is also important. Vehicles usually fail to attain free-flow speed at these times, and yet lower speed limits generate less changing friction, less speed dispersion and greater headways, which lead to fewer shock waves (Noland and Quilduras, 2005) and a reduction in both CO₂ and NOₓ emissions.

Orbital motorways present a great potential to reduce the environmental pressure of traffic in urban environments. Urban ring-roads have been constructed in cities all over the world, turning into major structuring elements in metropolitan areas (Martin et al., 2010) to manage the increasing flows between central cities and suburbs, and among suburbs themselves. In order to diminish the environmental impact of orbital motorways, especially of those running closer to the city centre, different strategies can be followed. Tunnels, like the one constructed in Madrid, diminish air pollutants and noise (Monzon et al., 2005). Nevertheless, congestion reduction strategies (e.g. real time travel information, ramp metering or speed management) have been advanced as cost-efficient solution to reduce traffic emissions (Chiquet, 1997; TRB, 2012). More research is needed in this field to better understand the impact of these kinds of measures both on the environment and on travel times.

The direct effect of lowering speed limits in reducing air pollutant emissions makes it especially interesting for motorways’ sections passing through highly populated areas. However, from the point of view of GHG emissions, this measure would be more effective if it were applied
to the whole ring-road. Transport emissions have a varying influence on the urban environment, due to the fact that air pollutants and GHG have different spatial impacts; therefore, this policy should be considered differently depending on the challenge. GHG emissions have minimal local effects, since urban GHG emissions substantially contribute to global figures, and hence to global warming (Health Effect Institute, 2010) and climate change. However, air pollutant emissions have a major local impact since they tend to affect the area or street where they are emitted (Gauderman et al., 2005; Health Effect Institute, 2010); their concentrations fall off rapidly with increasing distance from the road (e.g. Colville et al., 2001; Parra et al., 2009) and can be relatively short-lived. Air pollutants directly affect human health (WHO, 2003). Further research is required to understand the impact of this measure if applied to the whole ring-road, as well as on road sections with above-average traffic volumes where a reduction in emissions will have greater impact in aggregate terms.

Appendix 1. Madrid fleet composition used in the models

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Fuel</th>
<th>Technology</th>
<th>Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>≤1,4</td>
</tr>
<tr>
<td>Private vehicles 86,13%</td>
<td>Petrol 39,70%</td>
<td>PRE ECE (± 1971)</td>
<td>1.91%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECE 15/00-01 (1972–1977)</td>
<td>2.06%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECE 15/02 (1978–1979)</td>
<td>0.52%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECE 15/03 (1980–1984)</td>
<td>0.78%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECE 15/04 (1985–1995)</td>
<td>1.33%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO I</td>
<td>1.48%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO II</td>
<td>94/12/CE (1997–1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO III</td>
<td>98/69/CE S 2000 (2000–2004)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO IV</td>
<td>98/69/CE S 2005 (2005–2007)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Conventional (± 1992)</td>
<td>0.03%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO I</td>
<td>94/12/CE (1993–1996)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO II</td>
<td>94/12/CE (1997–1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO III</td>
<td>98/69/CE S 2000 (2000–2004)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO IV</td>
<td>98/69/CE S 2005 (2005–2007)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Fuel</th>
<th>Technology</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Light private vehicles &lt;3.5 t 8.55%</td>
<td>Petrol 1.59%</td>
<td>Conventional</td>
<td>0.97%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO I</td>
<td>93/59/CEE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO II</td>
<td>96/69/CE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO III</td>
<td>98/69/CE S 2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO IV</td>
<td>98/69/CE S 2005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Conventional</td>
<td>1.03%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO I</td>
<td>93/59/CEE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO II</td>
<td>96/69/CE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO III</td>
<td>98/69/CE S 2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EURO IV</td>
<td>98/69/CE S 2005</td>
</tr>
</tbody>
</table>

The model considers 94.68% of the vehicles in Madrid due to OD matrix constraints.

References


ECMT, 1996, Road Safety Speed Moderation, OECD Transport Research Center: European Conference of Ministers.


