AIRUSE

LIFE11 ENV/ES/584

Public Transport
Network in
Barcelona: Measures
to improve air
quality

Action B7

Coordinated by:













1. INTRODUCTION

Transports Metropolitans de Barcelona (TMB) is the main public transport operator in the Metropolitan Area of Barcelona with the stated mission of supporting citizens travelling within Barcelona. TMB offers two regular networks of transport, namely the bus and metro, as well as various other services such as the leisure routes that support tourism in the city (Barcelona Tourist Bus, Tram Blue and cable car). The aim of TMB can be summarized in three points:

- Meeting the needs of mobility and striving to make journeys on urban public transport more comfortable and with a faster displacement of citizens.
- Provide a public service accessible to everyone.
- Improve the quality of life in the metropolitan area of Barcelona cutting the travel time between different urban centres.

2. TMB BUS NETWORK

Of the 7,350,000 weekday commuting trips completed daily in the city of Barcelona 800,000 are by local bus transport. The TMB bus network comprises 112 lines, covering a total of 972 km and transporting 190 million passengers per year. To meet the European legislation in air quality and following the Air Quality Plan of the Catalonian Autonomous Government, TMB has considered and implemented several environmental alternatives for its fleet, including the use of biodiesel B30, compressed natural gas, hydrogen (fuel cell), electricity and hybrid technology. The organisation has adopted a proactive approach to environmental improvements, actively participating in numerous European projects from the 7th Framework Programme including ERRAC, ModSafe, SEAM4US and Seconomics, most of which are involved in promoting research on European travel safety and developing technologies to reduce energy consumption. TMB is also very active internationally, being present in various international organizations for public transport. This activity has increased with the recent renovation of the bus fleet, converting it into the cleanest in Europe (Fig. 1), with near 400 natural gas vehicles, 75 hybrids and the rest (near 500) with a combined



Selective Catalytic Reduction Trap and Continuously Regenerating Particulate Trap (SCRT) installed.

In July 2012 the company introduced twenty-five new hybrid (powered by electric motors) and thirty-five compressed natural gas buses, replacing sixty 14-year old diesel vehicles and in the process achieving emission reductions of 32.4 tons of annual NOx and 0.6 tons of particulate matter (PM). According to the current renovation plan for the TMB fleet the number of natural gas buses in 2015 will reach 500 vehicles (almost half of the total fleet, Fig. 2).



Figure 1: Enhanced Environmentally Vehicles (EVV) acquired by TMB, including buses run with compressed natural gas (top), standard hybrid (also converted diesel buses, middle) and bi-articulated hybrid (bottom).

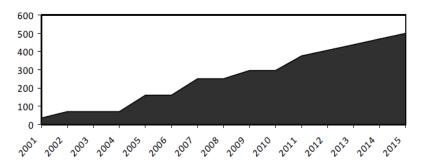


Figure 2: Evolution on the number of buses on natural gas in the TMB fleet across the first 15 years of this century.

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This renewal, together with the reforms implemented in the pre-existing bus fleet, has resulted in a total of 1,064 vehicles that can be considered clean according to European standards, since they all meet the standards Euro 4, Euro 5 or Euro 6 (which will come into force in 2015). Thus the new fleet (Fig. 1) is formed exclusively by vehicles classified as Enhanced Environmentally Vehicles (EEV), powered by compressed natural gas (39% of the fleet, including both standard and articulated buses), new and diesel converted hybrid (5%) or electrically powered with auxiliary heat engine as a generator, in accordance with reducing emissions of surface public transport and improve air quality in the metropolitan area.

The use of compressed natural gas in buses (CNG) reduces by 90% the NOx emission with respect to a EURO IV vehicle, and nearly in 100% in the case of particle emissions (Fig. 3). Hybrid buses on the other hand record a reduction on fuel consumption of 25-30%, reducing CO, CO2, NOx, SOx and particle emissions and noise, and resulting in an annual emission reduction of 17.1 tons of NOx and 0.3 tons less of PM. These buses have an average autonomy of 145 km, consuming 28.18 kg/100 km, which makes them a clean but expensive option. During 2013 three hybrid bi-articulated buses (25 m long and aesthetically similar to a tram) have been incorporated to the hybrid fleet, although their use is still in a test phase.

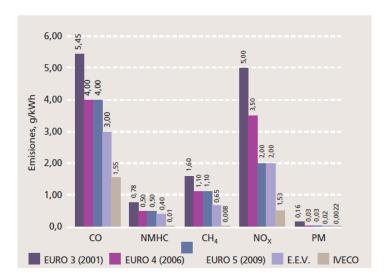
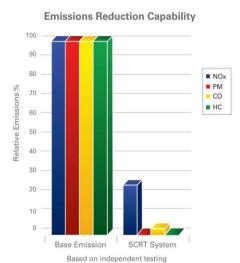


Figure 3: Comparison of factor emissions of CO, non-methane's hydrocarbons (NMHC), CH4, NOx and particles (PM) of Euro III, IV, V buses, Environmental Enhanced Vehicles (EEV) and compresses natural gas IVECO buses (from Querol et al., 2012a).

A plan has been also recently presented in collaboration with "Gas Natural Fenosa", involving the hybridisation of ten natural gas buses. This project is based on the addition of traction motors to produce what may result in the highest environmental quality vehicle currently on the road, as it will reduce emissions and save in fuel consumption (20% to 30% energy consumption and vehicle emissions, as compared to a bus of the same characteristics but unhybridised).

TMB has also developed another prototype within the Project Retrofit for the hybridization of existing diesel buses, allowing the environmental retrofit of forty diesel buses, visually distinguished by the "backpack" carried on their roof which contains the ultracapacitors that store the electricity (Fig. 1). Another, more widespread, approach has involved installing a





combined Selective Catalytic Reduction Trap and Continuously Regenerating Particulate Trap (SCRT) retrofit technology. This has already been installed on 435 units, with the effect of reducing annual emissions of NOx (71%) and particles (85%) for each bus. This technology (applied by the Eminox Company, http://www.eminox.es/) allows old Euro II vehicles to be upgraded to the latest Euro V standards, reducing legislated emissions of all pollutants from diesel motors (especially NOx and CO, Fig.4).

Figure 4: Reduction of air contaminants using SCRT technology (Eminox).

In general this renewal programme is producing clear and measurable decreases in the emissions of the TMB bus fleet vehicles, not only for particles but also for NOx emissions which have been shown to be reduced since 2010, especially due to the increasing number of GNC vehicles used (Fig. 5).

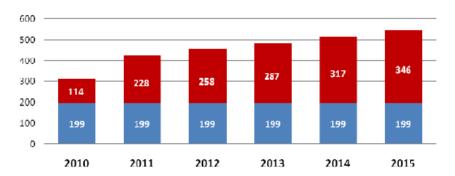


Figure 5: Reductions since 2010 of the NOx emitted by the TMB fleet (in tons/year) due to the implantation of SCRT (blue) and the use of GNC buses (red).

Most recently (2013) TMB has been working in collaboration with the Chinese company BYD to produce an electric bus which can be loaded in five hours and offers a driving autonomy of 200 kilometres, far enough to cover a full- service for an urban line. The bus, known as K9, has two 90 kW electric motors powered by a lithium battery and is currently

being tested for a period of two years in the city (Fig. 6). The action plan for 2010-2014 TMB considers the addition of more hybrid conversions from natural gas vehicles (depending on the availability of external funding), and more electric buses that could be charged in less time (down to 20 minutes) and have a longer autonomy (15 h). In order to achieve this the Barcelona City Hall has agreed to install two or three supply points to provide the necessary electricity recharge.



Figure 6: Prototype of electric bus being test by TMB.



In addition to the renovation of the bus fleet with more sustainable fuels, since 2012 TMB has been progressively implementing a new network system, involving 28 new lines (Fig. 7). The growth of the city during the last century has resulted in a bus service with a number of zigzag trajectories, duplication of routes, a high proportion of time with buses stopped in traffic lights and stops, heterogeneous geographic coverage of the city, and a loss of competitivity compared to the rail network. The new bus network is aimed to be quicker, easier to use, more modern, accessible, reliable and sustainable and offering real time information. The completed new network will consist of 17 "vertical" (sea-mountain) journeys, 8 "horizontal" (parallel to the coast line) and 3 "radial", crossing the others. With this network the journeys are more straight (favouring the speed and regularity of the journeys), the distance between stops is larger (350-400 m) and the lane for only buses will increase in length (with special own traffic lights).

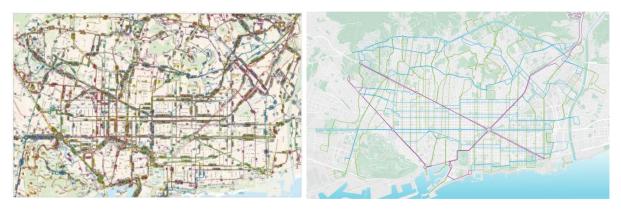


Figure 7: Barcelona TMB bus network in 2011 (left), and as planned from 2012 (right).

The gradual implementation of this more efficient and sustainable new model for the Barcelona bus network will allow important fuel savings (hybrid buses consume 25-30% less energy than non-hybrid vehicles), and will reduce emissions considerably, having repercussions on the air quality of the urban environment, not only in the most central located traffic hot spots but also on background levels.

3. TMB METRO NETWORK

Underground train systems are generally considered to be one of the most environmentally 'clean' forms of urban public transport. This positive evaluation of subway systems as environmentally desirable is due mainly to the following: a) the system is usually based on electric trains (with low direct emissions); b) it is energetically and environmentally efficient as it transports a large number of passengers (millions /day for example in megacities such as Tokyo and London); and c) underground transport favours a more fluid traffic on the surface, with correspondingly less congestion.

Over the last decade, however, a number of studies have cast a shadow over this clean image by revealing poor air quality in some metro systems. The main concern centres in high



levels of inhalable Particulate Matter (PM), which can reach several hundred $\mu g/m^3$. Key factors influencing metro PM concentrations will include station depth, date of construction, type of ventilation (natural/air conditioning), types of brakes (electric/conventional brake pads) and wheels (rubber v. steel) used on the trains, train frequency and more recently the presence or absence of platform screen door systems. Additional PM emission sources affecting indoor levels in metro systems include:

- Mechanical abrasion of rail/wheel and brakes and from the catenary (overhead line equipment).
- Resuspension of material caused by air turbulence in the stations and tunnels.
- PM emitted during night-time maintenance works, including use of traction fuel oil engines, construction works and welding dust.
- Cleaning activities.
- Surface air uptake from the surface, usually highly polluted by urban (mostly traffic) emissions.
- Sporadic incidents, such as flooding of tunnels with high sediment waters, and fires.

The TMB metro system in the city of Barcelona is one of the older underground transport systems in Europe with its first line beginning operation in 1924. By the present decade, the TMB comprises 8 lines (3 of them with driverless lines since 2009, Lines 9, 10 and 11) with a total length of 102.6 km and including 140 train stations (Figure 8). Trains run from 5 h in the morning until midnight during weekdays and Sundays, and for 24 h on Saturdays, with a frequency between 2 and 15 min, depending on the day (weekend or weekday) and time of day. Trains from all lines are equipped with an efficient air conditioning system that works continuously throughout the year, but with higher intensity in the summer period. Although commuting in Barcelona is mainly done by car (40%), the Barcelona metro absorbs a very important part of the urban commuting load, transporting around 1.25 million passengers on workdays (around 50% of the city's public transport). The most frequent average journey time is 35 min (approx 10.2 km round trip).



Figure 8: Barcelona TMB metro (and tram, T1-T6) network in 2013.

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The stations in the new lines differ radically from older lines in having single platforms in different tunnels with the platform being separated from the rail track by a wall with mechanical doors that are opened simultaneously with the train doors (known as platform screen door systems, Figure 9). The system is automatic, with a computer controlled driving system that optimises speeds, braking and stopping processes. The platforms also have a specific ventilation system that channels the convective dynamics caused by the train approach to renew the air throughout lateral ventilation outlets across the closed platform. This system allows air renovation in the platform, but also produces convective dynamics in the tunnel that may cause the resuspension of tunnel dust and the subsequent arrival of this dust to the platforms.



Figure 9: Platform design for both old (left, open platform) and new (right, platform screen door systems) subway lines in the Barcelona Metro system.

Recently TMB has started to measure air quality in the metro system in collaboration with the Institute of Environmental Assessment and Water Research (IDAEA-CSIC), comparing air quality levels in old and new lines, identifying main air pollutant sources, and studying possibilities of improving the ambient conditions in platforms and inside trains. This research is ongoing at the moment and is demonstrating that the new metro system of lines L9, 10 and 11 in the Barcelona city subway records ambient PM levels lower than in the conventional system by a factor of 2 to 3, which is probably attributable to the advanced ventilation set up, to the platform screen door system and other design features of the platform and trains, which reduce the contribution of metallic abrasion dust to ambient PM on the platform.

Although during the approach to the platform braking is electric, trains of both old and new systems use pneumatic braking after deceleration to a certain velocity to finally stop on the platform. Both systems use asbestos-free brake linings, but these are frontal to the wheel in old lines and lateral in trains of the new lines. The different composition of brake pads of these braking systems is responsible for much higher levels (by factors from 5 to 200 when compared to outdoor air) of metals such as Ba, As, Sr, Mo, Cu. The chemical speciation of PM sampled so far has allowed identifying 3 major sources of particles in the metros system: a) Brake wear; b) Outdoor air introduced into the metro; and c) Metal wear. Also the mineralogical characterisation by means of SEM and XRD has permitted the identification of laminar hematite (Fe_2O_3) as the dominant particle, being mainly originating from the mechanical abrasion of the rail track and wheels.





Levels of PM inside trains of the Barcelona city subway are around 3-4 times lower than in the platforms, being amongst the lowest reported for worldwide metro systems. This is most probably due to the air conditioning system working in all carriages of the Barcelona metro, although more studies inside trains are being currently taken to prove this.

Finally an assessment on PM exposure levels from different cities and transport modes is shown in Table 1 compared to the data obtained in the Barcelona metro so far.

	Car	Bus	Pedestrian	Motorbike	Cycle	Taxi	Metro
Mexico							
PM2.5		70					61
Houston							
PM3.5	35						
New York							
PM2.5							62
London							
PM2.5	36	39			30	33	246
Southampton, UK							
PM3.5					135		202
Manchester, UK							
PM4	42	338			54		
Belgian cities							
PM10	35-75				42-78		
Dublin							
PM2.5	83	128	63		88		
Florence							
PM2.5		33-75				20-70	
Munich							
PM10		137					
Taipei							
PM10	42	70		113			65
PM2.5	22	39		68			35
PM1	16	31		48			26
Hong Kong							
PM10		156				58	50
PM2.5		123					33
Guanzhou							
PM10						104	67
PM2.5							





			89	44
Barcelona metro				
PM10				
PM2.5				83
PM1				27
Barcelona metro (L9)				25
PM10				60
PM2.5				
PM1				19
1 1711				16

Table 1. PM exposure levels (in $\mu g/m3$) for different commuting modes in a number of cities of the world. From Querol et al (2012b) and references therein.

Accordingly to this table, commuting PM exposure in passenger cars reaches levels of 35-75 $\mu g P M_{10}/m^3$, 22-83 $\mu g P M_{2.5}/m^3$, comparable levels to those reported for metro commuting in Barcelona: 83 and 27 $\mu g/m^3$ for $P M_{10}$ and $P M_{2.5}$. $P M_{2.5}$ exposure levels during bus and cycling/motorbike commuting in these studies reached 33-128 $\mu g P M_{2.5}/m^3$ and 68-88 $\mu g P M_{2.5}/m^3$, respectively, markedly higher than in the Barcelona metro. Finally, the mean levels of $P M_{2.5}$ exposure during metro commuting in Barcelona obtained in the TMB/CSIC study are also lower than most of the exposure levels in worldwide metro systems (33-62 $\mu g P M_{2.5}/m^3$), with the exception of London (246 $\mu g P M_{2.5}/m^3$).

Further detailed studies in the TMB metro system are being presently carried out (2013-2014) in order to better understand the controls on air quality in the subway systems. For this a detailed database on particulate contamination of subway air is being obtained from a series of platforms and inside trains from 5 different metro lines. This database (including PM levels in a 0.5–20 µm size range and chemical and morphological characterisation of all PM) will make possible the establishment of levels and composition of PM in both platforms and inside subway trains under different conditions (e.g. new/old lines, ventilation systems, time of the day, air conditioning on/off), to observe size and morphology differences of the chemical components and to identify the main contributors to such levels and PM components. The results obtained after integrating all the new information will help future attempts to improve the air quality in subway systems worldwide, where billions of underground journeys are made annually, identifying the most appropriate correcting measures to reduce aerosol levels in this environment.









Institute of Environmental Assessment and Water Research (IDÆA)

Spanish Research Council (CSIC)

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All data here presented is based on a compilation of information obtained from TMB sources, except figure 3 from Querol et al., 2012a (Bases científico-técnicas para un Plan Nacional de Mejora de la Calidad del Aire. Informes CSIC. ISBN 978-84-00-09475-1. 349 pp.) and Table 1 from Querol et al. 2012b (Atmos. Chem. Phys., 12, 5055–5076).