**Supplementary materials**

**Environmental impacts of commuting modes in Lisbon: a life-cycle assessment addressing particulate matter impacts on health**

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# 1. Background

##  1.1 Environmental impacts of urban travel

Urban transportation has a diversity of environmental impacts, both global and local. On a global scale, it contributes significantly to dependence on fossil fuels (representing a risk in energy supply security), global warming and environmental degradation (Chester 2008; Woodcock et al. 2007). At the local scale, transportation affects citizens’ quality of life in social, economic and environmental ways (Albalate and Bel 2009), but its impact on health is a major concern. Health impacts associated with transportation in an urban context include urban air pollution, road-traffic injuries, physical activity, noise, and stress (Woodcock et al. 2007).

Air pollution associated with transportation is especially relevant in urban environments due to potentially high exposures and the consequent adverse effects on health (Chester 2008). The major local scale air pollutant emissions of concern associated with transportation include (Chester 2008; Nielsen 2013; Gorham 2002): (1) particulate matter (PM), which is generally classified by diameter as PM10 and PM2.5 (µm), and comprises of a mixture of small particles and liquid droplets that can affect cardiovascular and respiratory systems and cause and aggravate asthma, bronchitis, diabetes, lung cancer, adverse birth outcomes, other diseases, and reduced life expectancy and mortality; (2) carbon monoxide (CO), which reduces the oxygen-carrying capacity of the circulatory system, causing hypoxia, brain problems and even asphyxiation if exposures are high; (3) nitrogen oxides (NOx), which contribute to formation of ground-level ozone (O3) and which itself aggravates asthma and other respiratory diseases; (4) volatile organic compounds (VOC), which include a large number of compounds that evaporate at normal temperatures and which can cause headaches, nausea, central nervous system problems, and cancer, among other health problems; VOCs also contribute to O3. Other air pollutants associated with transportation include: (5) sulphur dioxide (SO2), which adversely affects the pulmonary, respiratory and cardiovascular systems, contributes to acid deposition (along with NO2) that causes multiple ecological impacts and forms secondary PM2.5, and (6) lead (Pb), which can impede brain development and causes anemia and kidney damage. Motor vehicle fuels in Europe and most other developed countries now have most of the sulphur removed, and lead is no longer used as a fuel additive, thus concerns related to SO2 and Pb emission have been greatly diminished.

## 1.2 Life-cycle studies of urban transportation

Many life-cycle assessment (LCA) studies of land-based transportation have been performed in the last decades. Most environmental assessments focused on personal transportation and explored new or alternative solutions (*e.g.*, alternative technologies, fuels, or eco-design strategies) to reduce impacts (Del Pero et al. 2015).

Due to the strong dependency of road transportation on fossil fuels and associated emissions, many life-cycle (LC) studies have assessed and compared potential technologies and fuel alternatives, such as biofuels, electric or hydrogen vehicles (e.g., Bartolozzi et al., 2013; Bauer et al., 2015). Hawkins et al. (2012) performed a literature review on environmental impacts of hybrid and electric vehicles, supporting that LCA was the preferred tool for comparing environmental impacts of transportation impacts. A large body of literature has provided comparative LCAs of internal combustion engine vehicles (ICEV) and electric vehicles (EV), namely hybrid electric vehicles (HEV) and battery electric vehicles (BEV), highlighting that the impacts of vehicles are heavily dependent on the use phase. Although EVs can perform better than conventional ICEVs in several aspects, the relative performance of electricity-based vehicles is strongly affected by the electricity mix used. In fact, if high-efficient ICEVs are considered, EVs do not present such advantages. Hawkins et al. (2012) added that the typical/average size of conventional ICEVs is generally larger than HEVs and EVs, which is likely to influence results.

Less research is available on the LCA of railway transportation. In Europe, Del Pero et al. (2015) performed an LCA of a heavy metro train in the area of Rome, including material acquisition, manufacturing, use and end-of-life, and showed that the use phase had the largest contribution. The study considered the vehicle kilometer traveled (VKT) as functional unit, and assumed passenger loads based on UNI EN 15663 (80% of seats occupied and 2.3/m2 standing). Impacts were calculated with CML2001 for abiotic depletion, acidification, eutrophication, eco-toxicity, GHG, human toxicity, ozone layer depletion, photochemical ozone creation and terrestrial eco-toxicity. The results indicated that potential approaches to increase environmental performance of the heavy metro train would be: reducing mass, increasing efficiency during operation, and increasing recyclability rate. Recently, an increasing number of EPDs has been published for railway transportation (trams, metro, regional and intercity trains (e.g., AnsaldoBreda 2011; Bombardier Transportation 2011). Electric rail transport is generally considered an efficient urban transportation alternative; however, its environmental performance is highly dependent on electricity generation mix and vehicle occupancy (Del Pero et al. 2015; Chester et al. 2012).

Regarding multi-mode comparative analyses, Stodolsky et al. (1998) compared at an early stage, rail and road modes for freight transportation. However, few other studies were found in the literature, besides the extensive work by Chester and colleagues on the LCA of transportation, developed in the last decade, mainly for the USA. Chester (2008) developed a comprehensive LC inventory for passenger transportation in the USA. Chester and Horvath (2009) calculated the LC energy and GHG emissions for buses, trains and airplanes in the US, including the supply chain and production of vehicles, infrastructure and fuel. The authors concluded that vehicle occupancy strongly affected the relative performance of these modes. Chester and Horvath (2010) conducted an LCA for the high speed rail (HSR) connecting four cities in the USA, comparing it with heavy rail transit, car and airplane traveling. This study emphasized again the influence of occupancy, and the best performance of railway transportation, when higher occupancies were considered. In another study, Chester et al. (2010) developed an energy and emissions inventory for three metropolitan areas in the USA. (San Francisco, Chicago and New York City), comparing automobile, diesel rail, electric rail and ferry, and including impacts associated with vehicle insurance, parking construction and maintenance. Energy and emissions were calculated for passenger mile traveled (PMT) and vehicle mile traveled (VMT), to provide comparability. Cars had the largest impact, accounting for over 85% of the regional energy and emissions, and the authors found that a LC perspective is highly significant in this context, as the overall environmental impacts of a transport service were up to 20 times those of vehicle operation. The authors also considered healthcare and greenhouse gas monetize externalities to evaluate the societal costs of passenger transportation. Chester and Horvath (2012) compared fuel-efficient and electric cars, with HSR and airplane traveling, to explore potential advances in technology, in California. Chester et al. (2013) performed a comparative LCA for the new rapid bus and transit light rail lanes in Los Angeles, considering energy consumption, GHG emissions and criteria pollutants (incl. potential for smog and respiratory impacts) and using both attributional and consequential LCA. The LCA included vehicle manufacture and maintenance, infrastructure construction and operation, and energy production components, but also vehicle and infrastructure insurance. PM and ozone were considered with impact characterization factors from TRACI model (Bare et al. 2002) to assess respiratory and smog stressors. The authors highlighted the importance of considering environmental boundaries beyond geopolitical boundaries; however, local (interurban) and remote emissions were added with no distinction in their potential effects, which depend on exposure. The LC water requirements of petrol cars, urban electric and regional diesel trains were compared with an input-output approach, in Melbourne, Australia (Stephan and Crawford, 2016). Recently, daily environmental impacts of the overall urban transportation in Lyon, France, were assessed in a study that integrated LCA and a land use and transport interactions (LUTI) model (François et al. 2017). The analysis comprised nine impact indicators, including particulate matter emissions in g PM10 eq inhabitant-1 day-1, which used the same characterization for exhaust emissions and emissions occurring in other life-cycle phases (e.g., vehicle manufacture).

Most previous LCAs of transportation modes compared alternative technologies within the same mode or a very limited number of modes, and focused on one or two environmental indicators (mainly energy use and GHG emissions). However, including a broader set of environmental indicators is crucial to identify and avoid unintended trade-offs in mitigation strategies (Chester et al. 2013; François et al. 2017). In addition, no studies were found providing a comprehensive LCA of alternative urban transportation modes in Europe and the integration of PM2.5 in LCIA needs to be improved. This paper presents a comprehensive multi-mode LCA comparing alternative transport modes for urban travel in the region of Lisbon, considering a broader range of impacts and integrating the impacts of PM2.5 emissions, and their effects on health.

## 1.3 Reducing environmental impacts of commuting

Strategies to reduce impacts associated with transportation, mostly focusing on energy use, emissions and congestion, have been implemented since the 1970s (Porter et al. 2013). In the last decades, many actions have been identified and explored in the literature, both addressing technological developments and travel behavior. One potential strategy is reducing the need to travel, e.g., reducing the number of trips by telecommuting, increasing vehicle occupancy and trip chaining (Woodcock et al. 2007). Other actions can reduce travel-related emissions and impacts without changing the modal mix and travel demand, e.g., efficiency increase due to improved engine design, emission controls, and renewable energy sources. This includes electric and hybrid vehicles, identified as a major short-term opportunity to improve fleet performance by reducing use-phase local emissions, although the entire life-cycle should be considered to assess the overall energy and resource use (Woodcock et al. 2007).

Banister (2008)identified four types of actions for reducing the environmental impacts of transportation: (1) reducing the need to travel; (2) transport policy measures; (3) land-use policy measures and (4) technological innovation. These strategies can reduce energy demand and environmental impacts and also improve access and equity (Woodcock et al. 2007). Porter et al. (2013) provided an extensive review and discussion on the underlying issues and effectiveness of specific actions to address and change travel behavior, namely focusing on travel reduction and efficient driving strategies (incl. road and parking pricing, transit improvements, telework, real-time traffic and parking information, speed limit reduction, etc.).

This paper performs a scenario analysis based on the strategies identified by Banister (2008), to assess their potential improvements and trade-offs in terms of environmental impacts associated with work travel. Work travel (commuting) represents a major portion of urban travel demand, and figures prominently in the literature and urban policies for this reason, as well as the congestion and pollution it can cause (Dong et al. 2016; Maat and Timmermans 2009; Strathman et al. 1994).

## 2. The life-cycle model: supplementary figures and tables

Figure S1 shows the 2011 transport mode mix for the Lisbon area and the residence parish (data refer to the main transport mode used).



Figure S1 – Commuting mode mix in 2011 in the great Lisbon area and in the residence parish (INE 2013)

Figure S2 shows the residence and workplace locations together with the main transportation infrastructure in Lisbon.



Figure S2 – Map of Lisbon: residence and workplace locations

Table S1 lists the vehicle types and technologies modeled for the use phase of road modes and respective share covered in the fleet.

Table S1 – Road transportation use phase: vehicle types and technologies modeled and share (%) covered in the Portuguese fleet (2013)

|  |  |  |  |
| --- | --- | --- | --- |
| Mode | Vehicle type/technology | EURO standards1 | Share (%) |
| Car | Gasoline, 0.8 – 1.4 l | 1 to 5 | 80 |
|  | Diesel, 1.5 – 2.0 l | 1 to 5 | 80 |
| Bus | Standard urban, diesel, 15 – 18 t | I to V | 90 |
| Motorcycles | 2-stroke, <50 cc | pre-EURO and I to III | 100 |
|  | 4-stroke, <250 cc, 250 – 750 cc, > 750cc | pre-EURO and I to III | 100 |

*1 The different notation used (Arabic and roman numerals) for passenger cars, buses and two-wheelers follows the legislation nomentaclature*.

## 3. Detailed results per person-kilometer traveled (PKT)

Table S2 – Detailed results per PKT: non-renewable fossil energy (NRE), greenhouse gas emissions (GHG), acidification (AC), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), PM2.5 intake and PM2.5 health.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **NRE** | **GHG** | **AC** | **TE** | **FE** | **ME** | **PM2.5 intake** |
|  |  | (MJ) | (g CO2 eq) | (molc H+ eq) | (molc N eq) | (kg P eq) | (kg N eq) | (10-6 mg) |
| **Passenger car, petrol** |
| Infrastructure | Construction | 0.1287 | 4.7177 | 3.12E-05 | 1.26E-04 | 9.30E-07 | 1.15E-05 | 73.2185 |
|  | Maintenance | 0.0712 | 5.6973 | 3.09E-05 | 4.50E-05 | 4.84E-06 | 5.32E-06 | 5.4387 |
|  | Disposal | 0.0008 | 0.0500 | 4.27E-07 | 2.02E-06 | 3.73E-09 | 1.84E-07 | 0.0738 |
| Vehicle | Manufacture | 0.2912 | 18.7675 | 1.47E-04 | 1.67E-04 | 1.46E-05 | 1.65E-05 | 20.1531 |
|  | Maintenance | 0.0789 | 3.5015 | 2.07E-05 | 2.92E-05 | 2.36E-06 | 2.99E-06 | 2.5877 |
|  | Disposal | 0.0096 | 1.8522 | 2.59E-06 | 6.46E-06 | 1.28E-07 | 6.15E-07 | 0.2575 |
|  | Operation | 2.3737 | 172.7286 | 4.71E-04 | 1.15E-03 | 4.59E-06 | 8.18E-05 | 340.8644 |
| **Passenger car, diesel** |
| Infrastructure | Construction | 0.1287 | 4.7177 | 3.12E-05 | 1.26E-04 | 9.30E-07 | 1.15E-05 | 73.2185 |
|  | Maintenance | 0.0712 | 5.6973 | 3.09E-05 | 4.50E-05 | 4.84E-06 | 5.32E-06 | 5.4387 |
|  | Disposal | 0.0008 | 0.0500 | 4.27E-07 | 2.02E-06 | 3.73E-09 | 1.84E-07 | 0.0738 |
| Vehicle | Manufacture | 0.2912 | 18.7675 | 1.47E-04 | 1.67E-04 | 1.46E-05 | 1.65E-05 | 20.1531 |
|  | Maintenance | 0.0789 | 3.5015 | 2.07E-05 | 2.92E-05 | 2.36E-06 | 2.99E-06 | 2.5877 |
|  | Disposal | 0.0096 | 1.8522 | 2.59E-06 | 6.46E-06 | 1.28E-07 | 6.15E-07 | 0.2575 |
|  | Operation | 2.2038 | 153.1905 | 6.03E-04 | 2.53E-03 | 3.44E-06 | 2.31E-04 | 1304.9558 |
| **Bus, diesel** |
| Infrastructure | Construction | 0.0886 | 3.2471 | 2.15E-05 | 8.70E-05 | 6.40E-07 | 7.92E-06 | 50.3948 |
|  | Maintenance | 0.0052 | 0.4123 | 2.24E-06 | 3.25E-06 | 3.50E-07 | 3.85E-07 | 0.3936 |
|  | Disposal | 0.0005 | 0.0344 | 2.94E-07 | 1.39E-06 | 2.57E-09 | 1.27E-07 | 0.0508 |
| Vehicle | Manufacture | 0.0255 | 1.8369 | 1.03E-05 | 1.73E-05 | 1.16E-06 | 1.66E-06 | 2.7738 |
|  | Maintenance | 0.0150 | 1.0178 | 4.35E-06 | 6.29E-06 | 5.97E-07 | 1.13E-06 | 0.5654 |
|  | Disposal | 0.0000 | 0.0695 | 2.09E-08 | 9.50E-08 | 9.58E-10 | 1.02E-08 | 0.0016 |
|  | Operation | 0.8111 | 56.4211 | 3.62E-04 | 1.74E-03 | 1.27E-06 | 1.59E-04 | 301.7336 |
| **Motorcycle, 2-stroke, petrol** |
| Infrastructure | Construction | 0.0255 | 0.9350 | 6.18E-06 | 2.51E-05 | 1.84E-07 | 2.28E-06 | 14.5111 |
|  | Maintenance | - | - | - | - | - | - | - |
|  | Disposal | 0.0002 | 0.0099 | 8.46E-08 | 3.99E-07 | 7.39E-10 | 3.65E-08 | 0.0146 |
| Vehicle | Manufacture | 0.1144 | 7.0038 | 5.92E-05 | 8.01E-05 | 3.86E-06 | 7.52E-06 | 7.2386 |
|  | Maintenance | 0.0886 | 4.8644 | 1.95E-05 | 3.72E-05 | 1.16E-06 | 3.50E-06 | 3.120162 |
|  | Disposal | 0.0023 | 1.3597 | 1.61E-06 | 4.34E-06 | 6.24E-08 | 4.30E-07 | 0.12437 |
|  | Operation | 1.1820 | 83.1799 | 2.85E-04 | 8.98E-04 | 2.29E-06 | 8.12E-05 | 2309.428 |
| **Motorcycle, 4-stroke, petrol** |
| Infrastructure | Construction | 0.0255 | 0.9350 | 6.18E-06 | 2.51E-05 | 1.84E-07 | 2.28E-06 | 14.51111 |
|  | Maintenance | - | - | - | - | - | - | - |
|  | Disposal | 0.0002 | 0.0099 | 8.46E-08 | 3.99E-07 | 7.39E-10 | 3.65E-08 | 0.014621 |
| Vehicle | Manufacture | 0.1144 | 7.0038 | 5.92E-05 | 8.01E-05 | 3.86E-06 | 7.52E-06 | 7.23859 |
|  | Maintenance | 0.0886 | 4.8644 | 1.95E-05 | 3.72E-05 | 1.16E-06 | 3.50E-06 | 3.120162 |
|  | Disposal | 0.0023 | 1.3597 | 1.61E-06 | 4.34E-06 | 6.24E-08 | 4.30E-07 | 0.12437 |
|  | Operation | 1.7611 | 124.6334 | 4.34E-04 | 1.39E-03 | 3.41E-06 | 1.26E-04 | 647.9598 |
| **Bicycle** |  |  |  |  |  |  |  |  |
| Infrastructure | Construction | 0.0136 | 0.4987 | 3.30E-06 | 1.34E-05 | 9.83E-08 | 1.22E-06 | 7.739264 |
|  | Maintenance | - | - | - | - | - | - | - |
|  | Disposal | 0.0001 | 0.0053 | 4.51E-08 | 2.13E-07 | 3.94E-10 | 1.95E-08 | 0.007798 |
| Vehicle | Manufacture | 0.0904 | 7.3778 | 4.49E-05 | 7.22E-05 | 3.05E-06 | 6.92E-06 | 10.36223 |
|  | Maintenance | 0.0191 | 1.2026 | 4.61E-06 | 8.96E-06 | 3.00E-07 | 8.69E-07 | 0.938188 |
|  | Disposal | 0.0004 | 0.3937 | 2.64E-07 | 1.22E-06 | 5.98E-09 | 1.19E-07 | 0.026684 |
|  | Operation | - | - | - | - | - | - | - |
| **Train, electricity** |  |  |  |  |  |  |  |
| Infrastructure | Construction | 0.0463 | 4.3070 | 1.93E-05 | 5.69E-05 | 1.83E-06 | 5.14E-06 | 8.606696 |
|  | Maintenance | 0.0099 | 0.7965 | 4.29E-06 | 6.06E-06 | 6.91E-07 | 6.86E-07 | 0.662349 |
|  | Disposal | 0.0124 | 0.7694 | 5.88E-06 | 2.77E-05 | 6.48E-08 | 2.53E-06 | 0.71231 |
| Vehicle | Manufacture | 0.0115 | 0.7801 | 6.24E-06 | 8.76E-06 | 1.21E-06 | 8.28E-07 | 1.299714 |
|  | Maintenance | 0.0024 | 0.1476 | 7.5E-07 | 1.81E-06 | 4.72E-08 | 2.09E-07 | 0.149974 |
|  | Disposal | 0.0000 | 0.0039 | 1.88E-08 | 9.31E-08 | 2.23E-10 | 7.13E-08 | 0.002123 |
|  | Operation | 0.6201 | 47.8297 | 0.00015 | 0.000518 | 2.01E-05 | 4.89E-05 | 22.76584 |
| **Subway, electricity** |  |  |  |  |  |  |  |
| Infrastructure | Construction | 0.0943 | 13.6010 | 4.41E-05 | 0.000137 | 3.23E-06 | 1.22E-05 | 15.90824 |
|  | Maintenance | 0.0093 | 0.7505 | 4.05E-06 | 5.71E-06 | 6.51E-07 | 6.46E-07 | 0.624036 |
|  | Disposal | 0.0117 | 0.7249 | 5.54E-06 | 2.61E-05 | 6.1E-08 | 2.39E-06 | 0.671108 |
| Vehicle | Manufacture | 0.0277 | 2.0761 | 1.24E-05 | 1.68E-05 | 1.43E-06 | 1.65E-06 | 2.229499 |
|  | Maintenance | 0.0218 | 1.2230 | 5.18E-06 | 9.39E-06 | 3.45E-07 | 9.81E-07 | 0.710091 |
|  | Disposal | 0.0000 | 0.0102 | 2.2E-08 | 1.01E-07 | 3.09E-10 | 2E-07 | 0.003308 |
|  | Operation | 0.5589 | 43.0828 | 0.000135 | 0.000467 | 1.81E-05 | 4.4E-05 | 20.51918 |

**5. Inter-study comparison of results**

Table S3 – NRE and GHG results per person-kilometer traveled (PKT) in this and previous studies in the literature

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Car | Bus | Rail | Motorcycle | Bicycle |
|  | NRE(MJ) | GHG(g CO2-eq) | NRE(MJ) | GHG(g CO2-eq) | NRE(MJ) | GHG(g CO2-eq) | NRE(MJ) | GHG(g CO2-eq) | NRE(KJ) | GHG(g CO2-eq) |
| Our study(Portugal) | 2.8 - 3.0 | 188 - 207 | 0.9 | 63 | 0.7 | 55 - 61 | 1.4 - 2.0 | 97 - 138 | 124 | 9.5 |
| Chester(2008)(USA) | 2.9 | 236.2 | 0.7 - 5.5(a) | 53 - 422(a) | 1.2 - 1.9(b) | 81 - 143(b) | 1.7 | 109 | - | - |
| Girardi etal.(2015)(Italy) | 3.1(c) | 205(c) | - | - | - | - | - | - | - | - |
| Ercan & Tatari (2015)(USA) | - | - | - | 140 - 196(d) | - | - | - | - | - | - |
| Cherry et al. (2009)(e)(China) | - | 268 | - | 151 | - | - | - | 154 | - | 6.3 |
| Sanchez et al. (2013)(d)(Spain) | - | - | 1.1 | 84 | - | - | - | - | - | - |
| Engelmoer (2012)(Netherlands) | - | - | - | - | - | - | - | - | 176 | - |
| Shibahara et al.(2013)(Japan) | - | - | - | - | - | - | - | - | - | 20(f) |

(a) the study provided peak and off-peak results, i.e., the authors distinguished a period of more intensive use and a low occupancy period

(b) the range covers result for five rail systems

(c) values adjusted to our vehicle service life and occupancy

(d) values derived from results per VKT assuming occupancy of 20 people

(e) values are for CO2 only, associated with production and use phases, and adjusted to our vehicle service lives and occupancy

(f) operational requirements considered additional food needs of the rider

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