



HAL
open science

Life Cycle Assessment to Support Decision-Making in Transportation Planning: A Case of French Bus Rapid Transit

Anne de Bortoli, Adélaïde Feraille Fresnet, Fabien Leurent

► **To cite this version:**

Anne de Bortoli, Adélaïde Feraille Fresnet, Fabien Leurent. Life Cycle Assessment to Support Decision-Making in Transportation Planning: A Case of French Bus Rapid Transit. Transportation Research Board 96th Annual Meeting Transportation Research Board, Jan 2017, Washington DC, United States. hal-01598921

HAL Id: hal-01598921

<https://hal.science/hal-01598921>

Submitted on 30 Sep 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **LIFE CYCLE ASSESSMENT TO SUPPORT DECISION-MAKING IN**
2 **TRANSPORTATION PLANNING: A CASE OF FRENCH BUS RAPID TRANSIT**

3
4
5 **Anne de Bortoli** (*corresponding author*)

6 MEng, MR, Ph.D. Candidate

7 Laboratoire Ville Mobilité Transport, Ecole Nationale des Ponts ParisTech, Université Paris
8 Est

9 Cité Descartes, 14 boulevard Newton, 77455 Champs-sur-Marne, France

10 Tel : +33 1 81 66 89 69 ; Email : anne.de-bortoli@enpc.fr

11
12 **Adélaïde Féraïlle**

13 Professor

14 Laboratoire Navier, Ecole Nationale des Ponts ParisTech, Université Paris Est

15 Cité Descartes, 6-8 Avenue Blaise Pascal, 77455 Champs-sur-Marne

16 Tel : +33 1 81 66 89 69 ; Email : adelaide.feraille@enpc.fr

17
18 **Fabien Leurent**

19 Professor

20 Laboratoire Ville Mobilité Transport, Ecole Nationale des Ponts ParisTech, Université Paris
21 Est

22 Cité Descartes, 14 boulevard Newton, 77455 Champs-sur-Marne, France

23 Tel : +33 1 81 66 89 69 ; Email : fabien.leurent@enpc.fr

24
25
26 Number of words, abstract : 249

27 Number of words, abstract, text and references: 5998

28 Number of tables and figures : 6 x 250 words

29 Total : 5998 + 1500 = **7498 words**

30
31
32
33 Date of submission: 11/15/2016

34

35

1 **ABSTRACT**

2
3 This article discusses the potential of Life Cycle Assessment (LCA) as a support tool for
4 decision-making in transportation planning.

5
6 After summarizing the LCA method, it applies it to a bi-articulated Bus Rapid Transit
7 system built around Fort de France, in Martinique, and a standard diesel bus rolling stock
8 alternative. The system boundaries include operation, and the vehicle and infrastructure
9 components. This case study forms the basis for discussions over the inclusion of LCA in
10 project processes, the issues and impediments, and its incorporation into mandatory Cost-
11 Benefit Analysis in France.

12
13 The results show the project's contributions to environmental impacts, captured via a set of
14 13 indicators. Bus fuel has a low impact on some indicators like solid waste or aquatic
15 toxicities but a substantial impact (35 to 57%) on acidification, eutrophication, and climate
16 change, demonstrating the importance of considering the entire system. With regard to
17 infrastructure, hubs account for 25% of impact, while lighting can be substantial (up to 20%).
18 Bi-articulated buses are a better option than standard diesel buses on most indicators under the
19 assumptions of this study. However, modal environmental performances are highly context-
20 sensitive. The impacts are normalized against those of the average passenger car, and
21 compared with those of high-occupancy car modes.

22
23 LCA could be used at every stage of project or policy design, with varying precision.
24 However, its implementation is restricted by several factors, notably understanding and
25 adoption by decision-makers, which are affected by issues such as results interpretation, extra
26 workload and lack of dedicated tools.

27
28
29
30 *Keywords:* Decision making support, Life Cycle Assessment, Transportation planning, Bus
31 Rapid Transit, Environmental alternative, rolling stocks, normalization
32

1 INTRODUCTION

2 3 **Context**

4 Transportation is very valuable to territorial socioeconomic development. Urban
5 populations are expected to go on rising in future decades, leading to a concentration of
6 mobility needs in cities. The objective of transportation planning is to meet, anticipate and
7 steer travel demand, through policy design and investment decisions. Standard selection
8 processes use a range of established methods, common to much of the international
9 community of transportation specialists. Cost-Benefit Analysis (CBA) in particular, also
10 called socioeconomic analysis, offers simple indicators like Net Present Value (NPV) to
11 assess project benefits.

12 Useful to society though it is, transportation is one of the biggest contributors to human
13 environmental stresses on the planet. In France, for example, transportation accounts for 20%
14 of greenhouse gas emissions (1). While some environmental impacts are taken into account in
15 CBA, given the growing importance of ecological factors, their role and representativeness
16 have to be addressed. In France, these effects encompass emissions of Greenhouse Gases
17 (GHG) and atmospheric pollutants (e.g. NO_x, PM_{2,5}, VOCs and SO₂) from operation, noise
18 and, more recently, some of the energy consumption. However, CBA omits other issues such
19 as resource depletion and waste, or damage to habitat (2). Moreover, the scope of CBA is
20 typically restricted to operation. On the contrary, Life Cycle Assessment (LCA) is a
21 multicriteria assessment methodology that takes into account broad-spectrum environmental
22 performance as well as the full physical system and life cycle of transportation modes.

23 24 **Objective and background**

25 The objective of this paper is to borrow from LCA the elements missing from the CBA
26 method of assessing the environmental performance of transportation modes in France, in
27 order to make the latter more holistic. A LCA case study is conducted on a French Bus Rapid
28 Transit project, to capture the impacts of infrastructure, vehicles, and operation. Two
29 alternative rolling stock types are presented. The key parameter of passenger travel demand is
30 discussed.

31 Applied to roads, LCA is now a fairly well-defined field ((3)), despite some difficulties (4).
32 It has sometimes been applied from a consequential perspective, which considers the impact
33 on operations of roadway condition or maintenance (4). Numerous LCAs have also been
34 conducted comparing bus operations ((5), (6), (7), (8), (9), (10)), excluding the nonoperational
35 components of vehicles. Very few Life Cycle Inventories (LCI) have been carried out on bus
36 body frames. EcoInvent provides the LCI of “standard” bus body frame production in Europe,
37 based on an Environmental Product Declaration for the Volvo 8500 bus, as well as standard
38 bus maintenance and end-of-life LCIs (11). Chester and Horvath (12) developed LCIs of
39 standard US buses, based on sales statistics. There are few references for LCAs on entire bus
40 modes ((11), (12), (13)), though one has covered a real Bus Rapid Transit (14) system with a
41 large perimeter, excluding end-of-life of infrastructure and vehicles. The bus body frame is
42 adapted from EcoInvent LCIs.

43 This article begins by summarizing the LCA framework and its key steps. It then goes on
44 to detail the case study of a French Caribbean BRT line by comparison with an alternative
45 vehicle, followed by an application of the assessment methodology together with an
46 explanation of the chosen set of 13 indicators. It then discusses the main findings of the case
47 study, before tackling the broader question of LCA as a potential aid to decision-making in
48 transportation planning.

49

LIFE CYCLE ASSESSMENT FRAMEWORK

Overview

LCA is a methodology used to estimate the material and energy flows – then the potential environmental impacts – of a system throughout its life cycle: extraction, transportation and processing of raw materials, system production, use/operation, maintenance, and end-of-life processing. It is covered by ISO standards 14 040 and 14 044 ((15), (16)). LCA results show the potential environmental impacts of the system from cradle to grave, in relation to a functional unit.

ISO standard 14040 defines the different steps in performing a LCA, which will be described later. Throughout this process and at each stage, the analyst needs to check, interpret, and monitor work in progress, in order to enhance the assessment and avoid mistakes.

Goal and scope

The first step is to define the objective of the study, in order to develop the best methodology for a given question. This objective will help set the boundaries for the system assessment and to pre-select environmental indicators (impact categories, damage).

At this stage, a functional unit is defined in order to quantify the system's function so that it can be compared with another system. The function of a transportation system is to carry passengers a certain distance, so an appropriate functional unit is the passenger-kilometer.

Inventory analysis (17)

Related to the functional unit, the inventory analysis is a quantitative description of inputs and outputs (emissions in the three different natural domains: water, air, and soil) going through the system, in the form of elementary material and energy flows. For generic processes, one can draw on Life Cycle Inventories (LCI) databases, for example 1 kWh LCIs for average electricity consumption in different locations. This means that a production inventory listing all quantified processes occurring during the life cycle of a system can be enough to conduct a LCA with an adequate LCI database.

Whether a LCI database is used or not, data collection is a long and unavoidable part of preparing a LCA.

Environmental impact assessment

The purpose of this step is to link flow inventories to the potential environmental impacts associated with what happens to those flows. To do so, characterization methods have been developed, based on cutting-edge knowledge in the different disciplines.

There are 2 mandatory steps in a LCI Assessment (LCIA) process (15):

1. selection of impact categories and classification: choice of environmental impacts relevant to the specifics of the study, assignment of elementary flows to impact categories;
2. characterization: application of “characterization factors” to every flow in each category, e.g. application of an “impact score” with a common unit in order to calculate an indicator.

This stage can be followed by two optional steps: normalization and weighting.

Interpreting an impact assessment

In addition to the analyst's continuous interpretation throughout the LCA process, the final step in the LCA is to interpret potential impacts, draw conclusions, and make

1 recommendations, in order to meet the initial goal. Caution is needed, as there are
2 uncertainties at every stage of the LCA process, which can lead to uncertainty over impacts.

3 **CASE STUDY: THE BUS RAPID TRANSIT PROJECT IN FORT DE FRANCE,** 4 **MARTINIQUE**

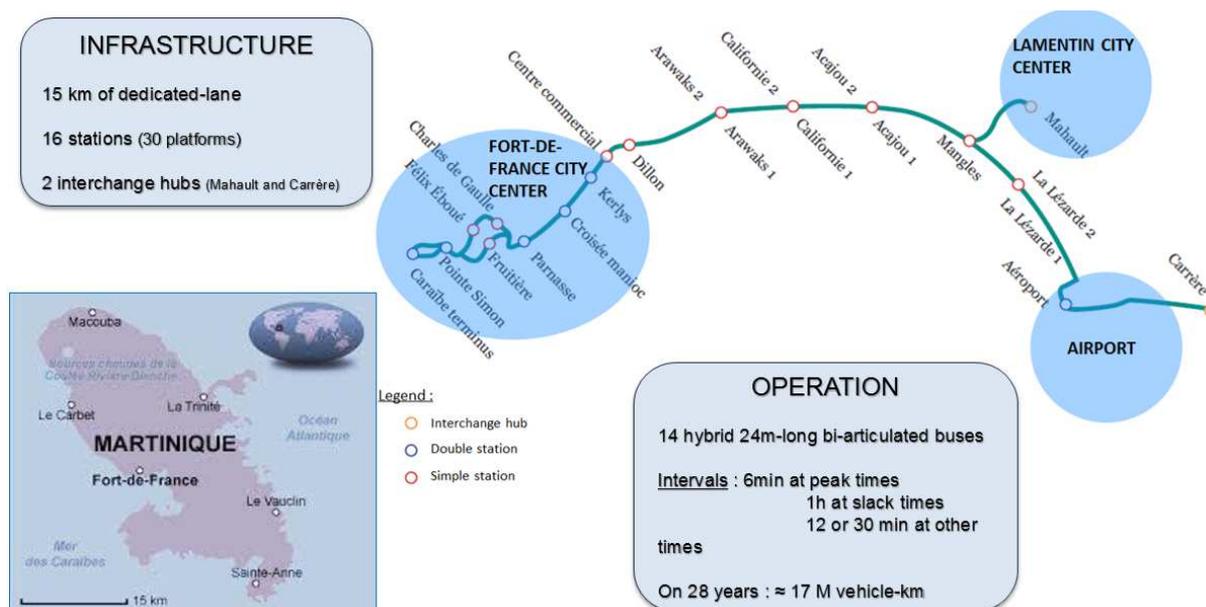
5 **Transportation planning context in Martinique**

6 The French island of Martinique is located in the middle of the Caribbean archipelago. Its
7 administrative capital, Fort de France, is home to almost 25% of the population and, with the
8 nearby town of Lamentin, accounts for half the island's employment (18).

9 According to the Household Travel Survey (19), around 70% of passenger trips are made
10 by car, rising to 83% in Fort de France. The occupancy rate of passenger cars is around 1.5
11 people per vehicle. Walking is a more common mode than public transit (number of trips).
12 As only 10% of people use public transit to commute, congestion has become a daily problem
13 at peak hours, particularly around Fort de France, where the concentration of activities is high
14 (20). This situation has prompted a number of transportation schemes, most recently the 2011
15 regional reform of Martinique Transportation, which promotes the use of public transit and
16 low environmental impact modes, the development of intermodality, and alternatives to single
17 occupancy vehicles (20).

18
19
20

19 **The Bus Rapid Transit project in Fort de France**



21
22
23
24
25
26
27
28
29
30
31
32
33
34

FIGURE 1 Principal information on the assessed transportation project

24 In response to these different planning orientations, a dedicated lane bus transit project was
25 launched few years ago. It was designed to reduce congestion on existing roads around Fort
26 de France, to offer an alternative to the existing unreliable and uncomfortable public
27 transportation provider “Taxico”, and to promote intermodal travel.

29 This forking line, running along a dedicated corridor for a distance of 15 km, will link the
30 center of Fort-de-France to the town of Lamentin and to the airport. It includes 16 stations and
31 2 interchange hubs, and will be served by 14 hybrid 24 meter-long bi-articulated buses with a
32 capacity of 140 passengers each (see main specifications in FIGURE 1). The line was set to
33 open at the end of 2015.

1 Whereas this article presents figures for an ex-post LCA with respect to physical
 2 components, and an ex-ante LCA with respect to operations, it aims to compare the type of
 3 vehicle chosen for this project with another type of rolling stock, as would have been possible
 4 during the project process, for instance in concept or preliminary designs.

6 *Bus vehicle alternative: standard diesel bus*

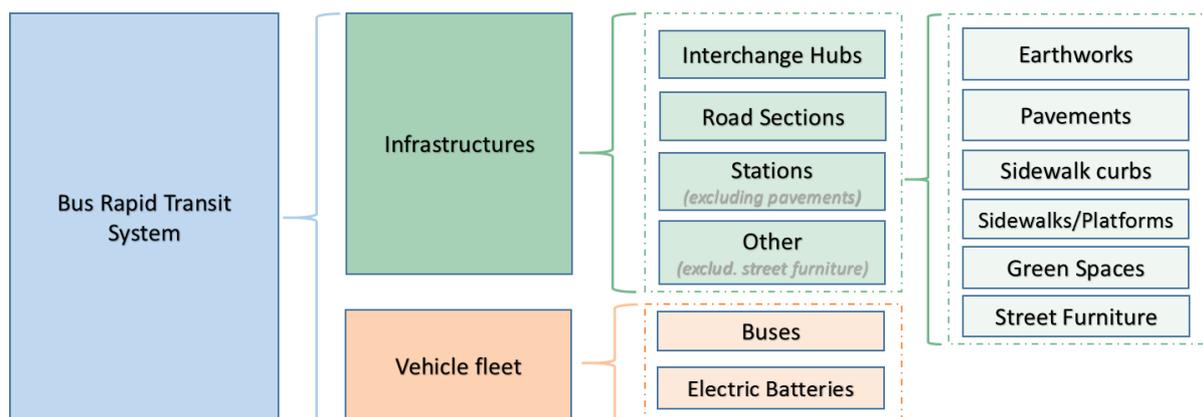
7 The alternative assessed is a 28 vehicle rolling stock of 13 meter long, standard diesel bus
 8 weighing 11 tons, with a capacity of 70 passengers. They are assumed to have the same 14
 9 year lifespan as the buses on the real line. This is low considering the potential mileage, but a
 10 high level of comfort is expected. Usually, such rolling stock is then reused in the regions,
 11 and then abroad, but these further leases of life are not considered here.

12 **METHODOLOGY**

13 This section provided a summary of the assessment methodology. Extensive details can be
 14 found in de Bortoli et al (21).

16 **System boundaries**

17 FIGURE 2 presents the line as modeled in the study. A very wide range of infrastructure
 18 has been considered, including green spaces, interchange hubs, and street furniture (including
 19 lighting). Interchange hubs include parking lots. For the vehicle fleet, electric batteries have
 20 been modeled separately.



22
 23 **FIGURE 2 Description of the system studied: model per subsystem (column 3) and**
 24 **per construction batch (column 4)**

26 The following elements were excluded in the absence of data: changing of lightbulbs,
 27 cleaning and maintenance of streetlamps; management and maintenance of green spaces and
 28 other street furniture like benches; incorporation of reclaimed asphalt pavement into new
 29 mixtures, and maintenance of the sidewalk curbs.

31 **Database and software**

32 We used EcoInvent 2.1, the benchmark European multi-topic database. It contains
 33 international industrial data from life cycle inventories on energy supply, resource extraction,
 34 chemical products, metals, agriculture, waste management services, and transportation
 35 services. LCIs have been reasonably adapted to the context of the project, in particular in
 36 terms of the transportation of materials and electricity supply.

37 We chose the OpenLCA 1.3.1 open source software, which allows users to adapt existing
 38 flows in EcoInvent. It has been particularly useful to create a specific process for the

1 operation of bi-articulated buses on the line, as consumption and emissions are completely
2 different from those of the existing bus process in EcoInvent.

3 4 **Data collection and assumption**

5 *Overview*

6 Data were collected through the participation of industrial companies involved in the
7 project, verified and/or completed by literature review and estimates by sectoral experts.

8 9 *Infrastructure*

10 This was assumed to be of entirely new construction, whereas in reality parts of the
11 infrastructure were already built. Usage of materials and construction machinery, energy
12 consumption and transportation are based on the Bill of Quantities and supplier information,
13 for instance in the case of lighting or transportation. Bitumen and plasticizers are from Europe,
14 whereas aggregates come from a quarry 3 km away.

15 16 *Chosen vehicle fleet*

17 The bus body frame is modeled using the EcoInvent process, based on a Volvo 8500 Low
18 Entry bus vehicle, including manufacturing of metal parts, engine production, and final
19 assembly in Europe. The Ecoinvent bus process excluding internal combustion engines has
20 been scaled up to the mass of the VanHool bus. The calculation has been modified compared
21 with de Bortoli et al (21) following a misinterpretation in the EcoInvent process description,
22 which corresponds to an 11-ton bus, but gives data based on the 18.4 ton Volvo 8500.
23 Moreover, the bus maintenance process has also been modified to match the Martinique
24 context with regard to the electrical mix used in garages.

25 The transportation of buses from Europe includes the 450 km from the manufacturing plant
26 in Koningshooikt, Belgium, to the Port of Le Havre in France, then 7000 km to the Port of
27 Fort-de-France by sea (EcoInvent process : “*operation, transoceanic freight ship*”).

28 Operation is modeled using the “*operation, regular bus, CH, [vkm]*” process, which
29 represents the operation of an average Swiss regular bus, modified with manufacturer’s data
30 based on consumption measured on a SORT cycle of 56L/100 km and NO_x, CO₂ and CO
31 emissions measured by the World Harmonized Stationary Cycle procedure

32 Batteries have been modeled on the basis of EcoInvent lithium-ion cells, and a package
33 extrapolated from Li et al (22).

34 35 *Alternative vehicle fleet*

36 The LCIs for these standard buses have been put together directly with EcoInvent
37 processes, excluding transportation and maintenance.

38 Buses run 200 km from the Volvo manufacturing plant in Säffle, Sweden, to the Port of
39 Gothenburg, then 7900 km to the Port of Fort-de-France by sea.

40 The electricity mix in the maintenance process has been modified.

41 42 **Selection of environmental criteria**

43 Hundreds of indicators can be calculated using LCA. As decision-making is harder the
44 more indicators there are, the set of indicators chosen in this study is presented briefly, with a
45 policy approach to the categorization proposal.

46 47 *Climate and energy*

48 **Energy consumption** Energy resource management is a fundamental environmental issue
49 for the 21st century. In this study, primary energy consumption is calculated in megajoule

1 equivalents, using the Cumulative Energy Demand method and combining all sources: wind,
2 fossil, water, primary forest, solar, biomass, geothermal and nuclear energies.

3 **Climate change** As this is a major environmental concern, the indicator selected uses the
4 2001CML characterization method (Institute of Environmental Sciences - Leiden university),
5 based on the Intergovernmental Panel on Climate Change's global warming potentials for a
6 100-year time horizon, in CO2 equivalents.

7 **Stratospheric ozone depletion** Stratospheric ozone works as a shield that reflects a
8 proportion of ultraviolet radiation (UVR) away from the Earth: it reduces global warming and
9 protects people from the harmful effects of UVR. The transportation sector is responsible for
10 a significant proportion of depletion through air conditioning and refrigerating systems. The
11 CML method provides an indicator for calculating stratospheric ozone depletion expressed in
12 kilograms equivalent of Freon-11 (CFC-11).

13 *Resources and waste*

14 **Depletion of abiotic resources** Rapid societal development is leading to a shortage of
15 abiotic resources. Aggregates are already scarce in some French regions. Reducing resource
16 consumption is a priority for sustainable development, and is expressed with a CML indicator
17 in kilograms equivalent of antimony.

18 **Solid and radioactive waste** In a context of increasing resource consumption, reducing
19 waste by repurposing is important. An indicator for solid waste production is calculated using
20 the EDIP characterization method and adding different landfill waste masses: bulk waste, slag
21 and ashes, as well as hazardous waste. A special indicator on radioactive waste is also
22 calculated directly with EDIP, as energy pathways are of interest in current policies and relate
23 to transportation policy choices.

24 *Health and ecosystems*

25 **Human toxicity** Increases in toxicity in the human environment is a public health issue
26 that requires evaluation. A CML indicator on human toxicity is selected, expressed in
27 kilograms equivalent of 1,4-DCB on a time horizon of 100 years.

28 **Photochemical oxidation** Occurring as summer smog, photochemical oxidants are
29 secondary air pollutants that cause damage to plants (23) and as well as a range of human
30 health disorders (24). Since their complex chemical formulae include nitrogen oxides and
31 reactive hydrocarbons, they are an obvious indicator for transportation assessment. A CML
32 indicator (high NOx) in kilograms equivalent of ethylene is proposed.

33 **Ecotoxicity** Three indicators for ecosystem toxicity are proposed, based on the CML
34 method and using the same units as for the human toxicity indicator: terrestrial, marine
35 aquatic and freshwater aquatic ecotoxicities. This choice represents toxicity of soil and waters.

36 **Eutrophication potential** Excessive discharges of rich nutrients into a body of water can
37 lead to excessive plant growth, which destroys ecosystems by consuming sunlight, space, and
38 oxygen. As this can totally devastate ecosystems and have a direct effect on toxicity (even for
39 humans), a CML indicator has been selected, for a generic location, in kilograms equivalent
40 of phosphate.

41 **Acidification potential** This encompasses potential acidity increases in water as well as in
42 soil caused by the deposit of atmospheric acids mainly through rainfall. The main sources of
43 acidification are industries, vehicle traffic, and power plants. The CML indicator for generic
44 location has been used in this case study, in kilograms equivalent of sulfur dioxide.

EVALUATION RESULTS

Potential environmental impacts of the real transportation service

Complete system

As shown in FIGURE 3, the majority of environmental impacts are due to bus life cycles:

- especially toxicity impact from nonoperational bus components, which account for between 30 and 55% of total impacts. These are primarily caused by aluminum, chromium, copper, and motor resistors;
- fuel accounts for between 35 and 57% of eutrophication (mostly due to nitrogen oxides), photochemical oxidation (50% due to atmospheric emissions of sulfur dioxide, formaldehyde, and acetaldehyde), stratospheric ozone depletion (99% due to bromotrifluoromethane atmospheric emissions), acidification (80% due to nitrogen oxides), climate change (95% from carbon dioxide emissions), abiotic resources (92% from crude oil), and energy consumption

Nevertheless, infrastructure (including green spaces) contributes substantially to environmental burden, from 20% for aquatic toxicities to 75% for radioactive waste. The impact of pavement is particularly high, but components that typically lie outside the scope of LCA, such as green spaces, street furniture, sidewalks, and platforms, are not insignificant, accounting for between 5% (stratospheric ozone depletion) and 20% (terrestrial ecotoxicity) of impacts.

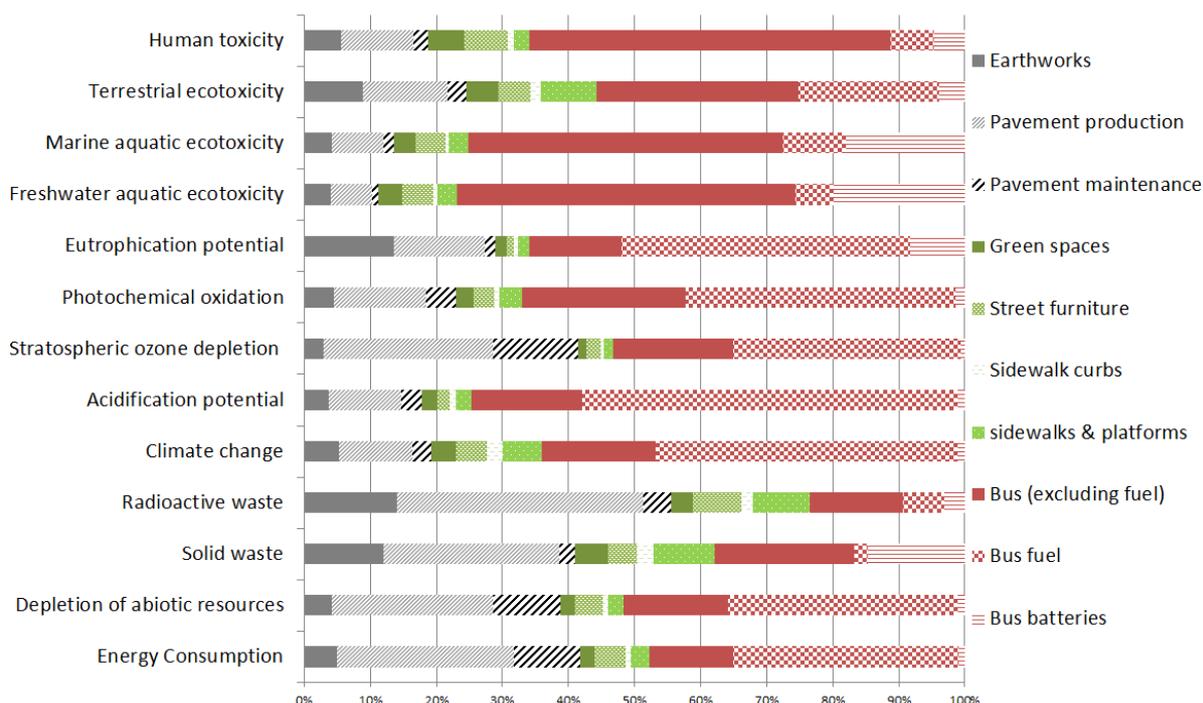
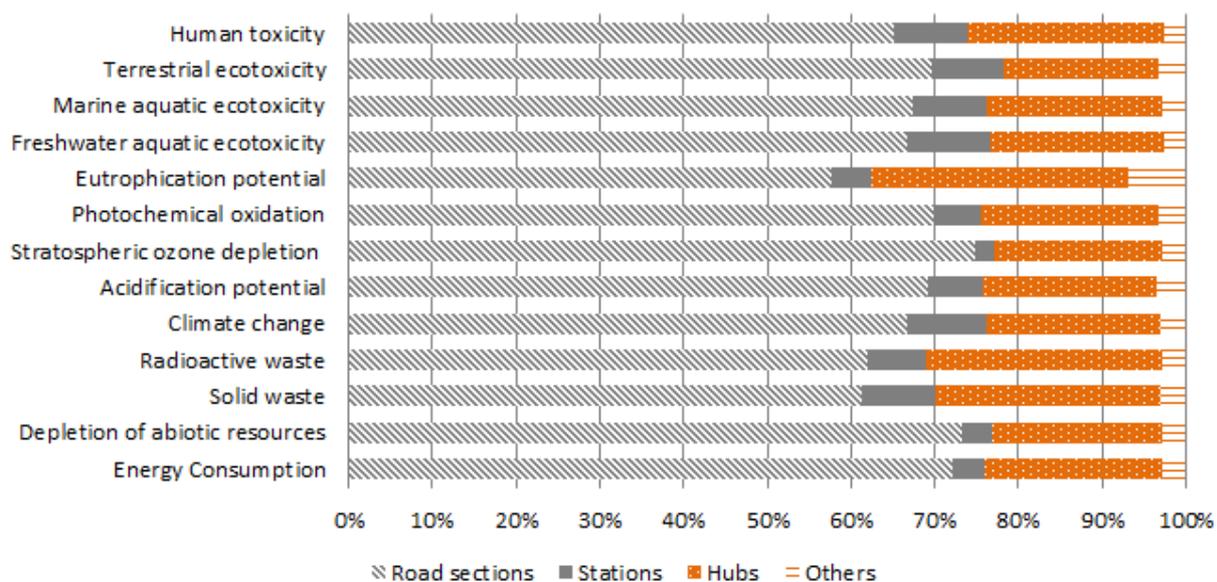


FIGURE 3 Subsystem contributions to potential environmental impacts

Infrastructure

Among infrastructural subsystems, road sections account for the major proportion of the impacts, between 60 and 75%. Nevertheless, as authors have noted (14), other subsystems are not insignificant: while stations represent 2 to 10% of the impacts, hubs are substantial, accounting for 20 to 30% of environmental burdens.



1
2 **FIGURE 4 Contribution of the different infrastructural subsystems to different**
3 **impact categories**

4
5 *Street furniture*

6 This item includes the production of the equipment in Europe, transportation to Fort de
7 France, and electricity consumed by streetlamps and access barriers.

8 In Figure 3, only 20% of lighting impacts have been allocated to the BRT line, given that it
9 also benefits users of adjacent mixed-traffic lanes. Otherwise, with one streetlamp every 50m,
10 a lighting system can account for up to 20% of line impacts over 28 years in energy
11 consumption, climate change, or natural resource depletion. These impacts largely depend on
12 the electricity mix: the use phase is predominant, accounting for 45 to 95% of impacts in
13 terms of electricity consumption alone.

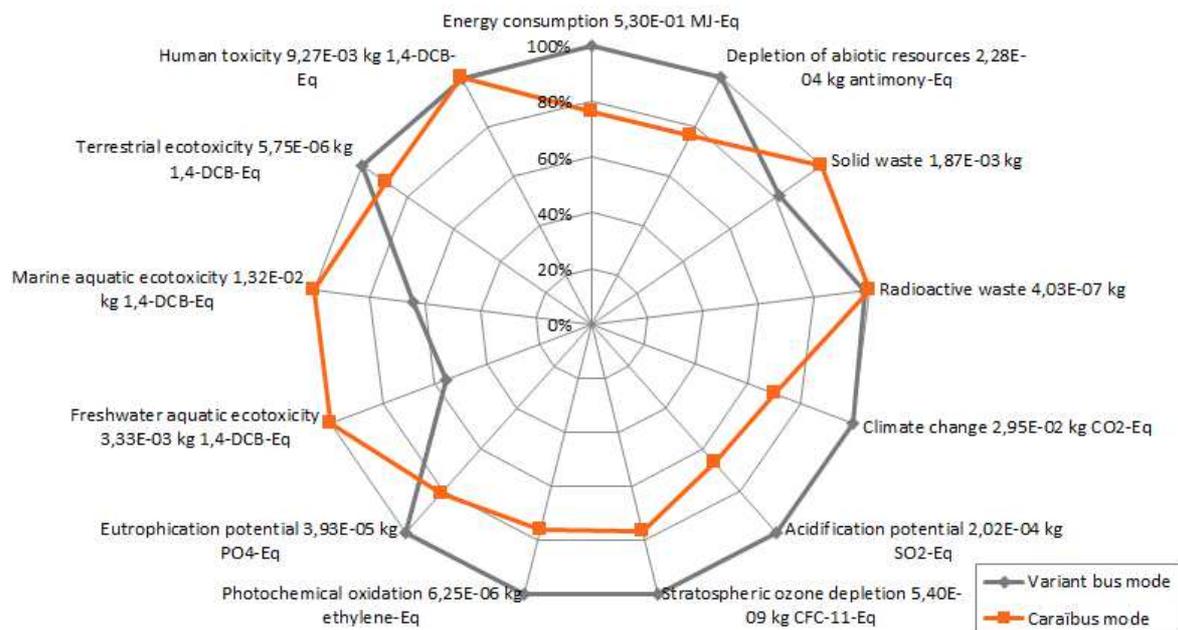
14 Although the street furniture comes from France, the overall impact of transportation is
15 negligible.

16
17 **Comparison of bi-articulated hybrid buses with standard diesel buses**

18 Based on 100% occupancy over 28 years, the best vehicle option depends on the indicator
19 (FIGURE 5): bi-articulated buses are better on every indicator except marine and freshwater
20 ecotoxicities, and solid waste. The two options are similar on radioactive waste and human
21 toxicity performance.

22 As ecotoxicities are mostly related to metals, it would be of interest to refine the data
23 collection and LCIs on propulsion systems.

24



1
2 **FIGURE 5 Environmental impact comparison of bi-articulated hybrid bus mode**
3 **with standard diesel bus variant mode**
4

5 Even though the performance ranking per indicator remains the same when comparing the
6 impacts of rolling stock life cycle and modes, relative impact differences tend to diminish
7 compared with vehicle-only life cycle comparison. The infrastructure contribution for these
8 bus modes is quite high compared with shared lane modes, where infrastructure accounts for
9 only a few percent of the impacts on energy consumption and climate change (25). Indeed,
10 dedicated-lane roads are less intensively used – Annual Average Daily Traffics (AADT) are
11 between 54 and 72 buses for the Caraibus mode and between 108 and 144 for the alternative
12 standard bus mode over 28 years – than shared roads used by an average passenger car mode,
13 with AADTs ranging from the thousands to the ten thousands.

14 DISCUSSION

15 LCA for transportation systems: what challenges?

16 *Assessment of complex systems: systemic approach and contextualization*

17 Assessing complex systems is difficult: capturing the interactions and feedbacks between
18 subsystems may be hard, demands transdisciplinary research, and is globally time consuming.
19 The partial or complete omission of interaction and subsystem feedbacks may lead to
20 mistakes in quantifying environmental impact, and therefore to misleading input into
21 decision-making.

22 Moreover, context-specific data and modeling are particularly important in reducing the
23 variability of results and providing environmental assessments relevant to decision-making
24 (26). However, they are very time-consuming and a possible source of error when using
25 generic LCI databases, characterization methods, and LCA software. Choosing the right
26 characterization method is an important step toward contextualization, but is still tricky,
27 particularly in very particular conditions, such as those of a Caribbean island.

28 *A need for traffic microsimulation*

29 In ex-ante transportation appraisal, accurate traffic simulation forecasts are essential in
30 order to quantify the occupancy rates for a functional unit. Here, a 100% occupancy rate has
31 been considered, e.g. full capacity. In fact, as demand rises with higher frequency, demand on
32 bi-articulated and standard buses is unlikely to be the same. Although other factors such as
33

1 ticket price, modal image, or comfort also affect traffic demand, standard bus demand is
 2 likely to be higher since frequency on the standard bus mode is twice as high as for the bi-
 3 articulated bus mode. Defining occupancy rate scenarios is possible, even advisable, when
 4 conducting comparative LCAs for transportation modes ((30), (21)). Nevertheless, this is not
 5 sufficient in this case study, which requires traffic microsimulation.

6 Microsimulation would also be needed to assess the impact of doubling bus traffic on the
 7 rest of the network. Indeed, as buses have priority at traffic signals, vehicles in other lanes are
 8 affected, possibly increasing the total environmental burden. These side-effects can be
 9 captured either by enlarging the system boundaries or by conducting a consequential LCA.

10 *Other biases*

11 The alternative does not consider the impact of the vehicle type on infrastructural design
 12 and maintenance, whereas pavement design is based on expected heavy vehicle axle loads,
 13 using Burmister models.

14 Moreover, the impact of passenger load on fuel consumption has not been explored.

15 In addition, BRT systems entail a high level of service, meaning good passenger comfort.
 16 In Martinique, capacity is only 140 passengers, whereas a 24m-long bus can accommodate
 17 around 200 passengers. If demand is high, the BRT line would be more environmentally
 18 efficient with fewer seats.

19 **LCA as a tool for supporting decisions on transportation planning**

20 *Background*

21 LCA is only occasionally used as an aid to decision-making on transportation issues. In
 22 recent years, eco-comparators have been developed in France to compare road pavements
 23 based on a truncated LCA (28). They can be used in bidding processes if environmental
 24 alternatives are allowed. Nevertheless, system boundaries miss out the key environmental
 25 impacts relating to vehicle-pavement interaction (29). LCA-based tools are used by some
 26 companies in Europe to improve the mobility practices of employees (13). Transportation
 27 projects have been assessed by some authors, in particular in California ((30), (14), (27)).
 28 Some decisions, though driven by environmental objectives, are taken without performing a
 29 LCA, such as policies in favor of e-mobility. The case of Paris, which is planning to convert
 30 its entire bus rolling stock to e-buses, is emblematic. Indeed, while e-mobility is currently
 31 seen as an obvious way to reduce GHG emissions from transportation in France, a massive
 32 change in electricity consumption – and therefore supply – might change this assumption, and
 33 could be captured by a consequential LCA. LCA on alternative mass transit bus powertrain
 34 solutions has already been used to produce recommendations, for instance in the United
 35 States, relating to the electricity grid (9). Nevertheless, LCA is not sufficient for the
 36 assessment of e-mobility, notably two of its main urban benefits, i.e. reducing air and noise
 37 pollution. The latter is not yet assessed in LCA ((31), (32)).

38 *At what stage(s) of transportation development?*

39 **At the project level** LCA can be used at each stage of the project process, with different
 40 levels of precision, to aid decision-making on environmental performance. As illustrated in
 41 this article, ex ante LCA can be performed to choose between technical options. Nevertheless,
 42 it demands expertise as well as caution to model likely scenarios. Moreover, since it comes on
 43 top of a tough appraisal process – including environmental impact assessment, CBA, and
 44 other analyses – it can be perceived as additional workload. This is especially true with regard
 45 to the current lack of LCA-based decision tools in the transportation field, by contrast with the
 46 building sector which is significantly ahead in the development of sectoral tools.

1 **For policies** Before the start of projects, in the policy design phase, attention should be
2 paid, as already said, to travel demand and occupancy rates, in order to avoid condemning or
3 approving embryonic transportation modes without regard for the specifics of the context
4 ((30)). In FIGURE 6, it is interesting to note that with three people in a car, a European
5 passenger car mode is more efficient on most indicators than the two public transit modes in
6 Martinique with a 50% occupancy rate. For a specific context, however, a systemic approach
7 is called for, taking network effects into account, since multimodality is now standard in
8 urban trips.

9
10 *Adoption of multicriteria results by decision-makers*

11 One of the difficulties in using LCA results to support decision-making is the multicriteria
12 aspect: teaching skills and communication are important when presenting a number of
13 indicators over which there is some uncertainty. Indeed, climate change and energy resources
14 are not the only environmental issues.

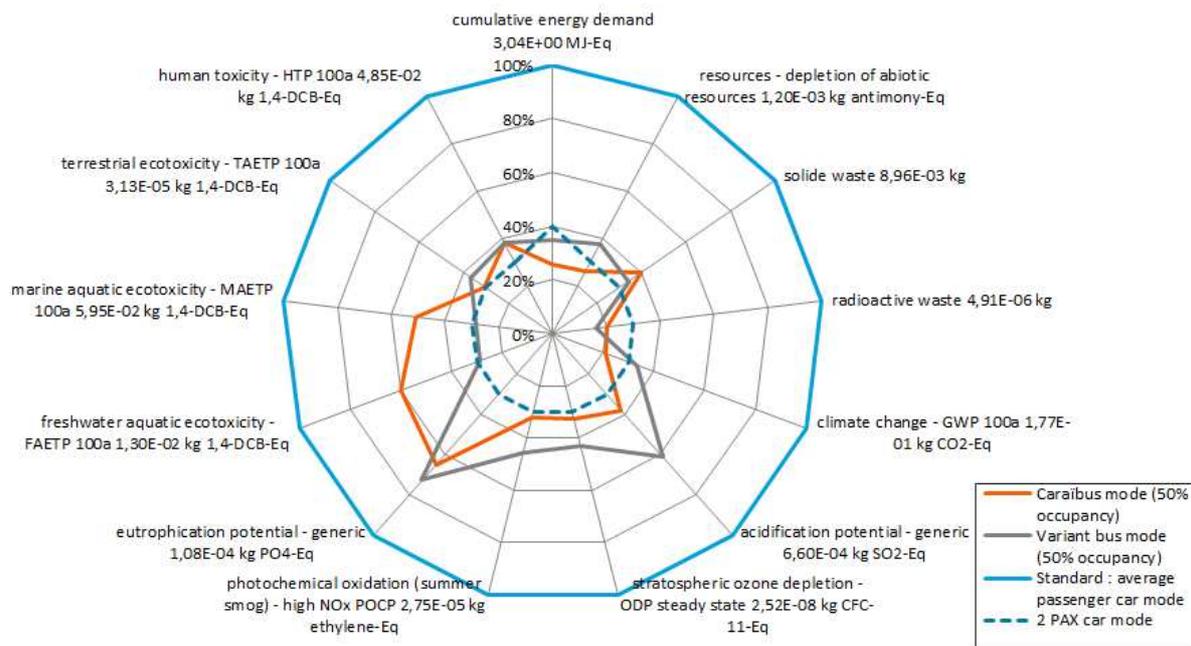
15 When it comes to visualizing results, questions arise, e.g.: are spider charts sufficiently
16 comprehensive? Are histograms clearer? Are there better diagrams? How many indicators can
17 reasonably be presented simultaneously? In the case of multiple indicators, should criteria be
18 packaged by theme or ranking? Comparisons of multiple scenarios are even trickier for LCA
19 analysts to present.

20
21 *Interpretation of figures*

22 As there can be multiple indicators, with unfamiliar units, decision-makers can find the
23 results hard to understand. On top of this, impact figures and their relative importance seem to
24 be a hotspot.

25 One option in the LCA framework is to normalize results, i.e. to compare them with a
26 standard, which gives the order of magnitude for the different impacts. In the transportation
27 sector, where passenger car transportation is the dominant mode, normalized results are
28 presented on the basis of the impacts of this mode (average occupancy 1.2), a standard that
29 could also be spatialized to be more meaningful. Introducing this specific standard would be a
30 positive way to encourage the use of LCA as a decision support tool, as the passenger car
31 mode has the highest impact: alternatives would always be better.

32
33
34



1
2 **FIGURE 6 Environmental comparison of the BRT mode (50% occupancy), the**
3 **standard bus alternative mode (50% occupancy), and a proposed normalization**
4 **standard: the European average passenger car mode**
5

6 On the other hand, developing a more challenging standard, for instance including existing
7 environmental transportation targets for every indicator in the normalization standard, would
8 be more ambitious. Nevertheless, for some impacts there are no official targets.
9

10 Use of LCA in the standard cost-benefit analysis

11 *Monetization of LCA impacts*

12 Since performing LCA requires a significant investment of time, incorporating it into
13 France's compulsory CBA could be a helpful compromise to achieve a better representation
14 of environmental burdens in transportation assessments. CBA uses tutelary values to monetize
15 every externality, whereas there are a dozen valuation methods for monetizing some LCA
16 impacts, all based on different approaches (33). Integrating LCA into CBA would require to
17 make coherent monetization methods as well as boundaries.
18

19 *Impact of weighting in decision-making*

20 The choice of tutelary values has a significant impact on results, because it entails a
21 weighting process. In CBA for transportation projects, travel time cost effects are usually the
22 dominant factor in the Net Present Value of projects. Carbon dioxide emissions are already
23 taken partially into consideration, but are mostly insignificant with current tutelary values. If
24 tutelary values do not show the environmental burden in NPV, there is no point in including
25 LCA indicators in CBA.
26

27 CONCLUSIONS

28 Even though environmental burden is a common component of decision-making processes,
29 assessment practices rarely properly quantify it. In fact, CBA does not reflect ecological
30 concerns. LCA could be used to clarify environmental performance, but remains a tool that is
31 used only occasionally. In France, environmental alternatives are not always accepted in
32 tendering processes. Some companies seem to be interested in LCA as a decision support tool,
33 but regret the lack of public policy direction or incentives.

1 Moreover, the compulsory ministerial CBA process is already complex, and French
2 practitioners are still working on the application of a new circular. In these circumstances, it is
3 difficult to convey the importance of adding LCA criteria that are not addressed in the CBA
4 appraisal protocol. Nevertheless, LCA can be seen as a way to achieve multi-stakeholder
5 consensus, on account of the wide spectrum of environmental impacts it encompasses.

6 7 **AKNOWLEDGEMENTS**

8 This work was funded by the ParisTech-VINCI Chair “Eco-design of buildings and
9 infrastructures”, a collaborative five-year research program started in 2008 and renewed in
10 2013, conducted by École des Ponts ParisTech, Mines ParisTech, and AgroParisTech, with
11 the sponsorship of VINCI. We would also like to thank Emmanuel Berthet from Caraïbus,
12 VINCI, who helped us to connect with involved companies to conduct the huge data
13 collection that underpins this case study.

14

1 **REFERENCES**

- 2 (1) “Key Figures on Climate France and Worldwide - 2016 Edition.” Highlights. French
3 Ministry for the Environment, October 2015. [http://www.statistiques.developpement-](http://www.statistiques.developpement-durable.gouv.fr/fileadmin/documents/Produits_editoriaux/Publications/Reperes/2015/highlights-key-figures-climate-2016-edition.pdf)
4 [durable.gouv.fr/fileadmin/documents/Produits](http://www.statistiques.developpement-durable.gouv.fr/fileadmin/documents/Produits_editoriaux/Publications/Reperes/2015/highlights-key-figures-climate-2016-edition.pdf)
5 [editoriaux/Publications/Reperes/2015/](http://www.statistiques.developpement-durable.gouv.fr/fileadmin/documents/Produits_editoriaux/Publications/Reperes/2015/highlights-key-figures-climate-2016-edition.pdf)
6 [highlights-key-figures-climate-2016-edition.pdf](http://www.statistiques.developpement-durable.gouv.fr/fileadmin/documents/Produits_editoriaux/Publications/Reperes/2015/highlights-key-figures-climate-2016-edition.pdf).
7
8 (2) Quinet, Emile. “L’évaluation Socioéconomique Des Investissements Publics - Rapport
9 Final,” 2013.
10 (3) Santero, Nicholas J., Eric Masanet, and Arpad Horvath. “Life-Cycle Assessment of
11 Pavements. Part I: Critical Review.” *Resources, Conservation and Recycling* 55, no.
12 9–10 (July 2011): 801–9. doi:10.1016/j.resconrec.2011.03.010.
13 (4) ———. “Life-Cycle Assessment of Pavements Part II: Filling the Research Gaps.”
14 *Resources, Conservation and Recycling* 55, no. 9–10 (July 2011): 810–18.
15 doi:10.1016/j.resconrec.2011.03.009.
16 (5) Kliucininkas, L., J. Matulevicius, and D. Martuzevicius. “The Life Cycle Assessment
17 of Alternative Fuel Chains for Urban Buses and Trolleybuses.” *Journal of*
18 *Environmental Management* 99 (May 2012): 98–103.
19 doi:10.1016/j.jenvman.2012.01.012.
20 (6) Simon, B, L Tamaska, and N Kovats. “Analysis of Global and Local Environmental
21 Impacts of Bus Transport by LCA Methodologies.” *Hungarian Journal of Industrial*
22 *Chemistry*, 2010, 38 edition.
23 (7) Ally, Jamie, and Trevor Pryor. “Life-Cycle Assessment of Diesel, Natural Gas and
24 Hydrogen Fuel Cell Bus Transportation Systems.” *Journal of Power Sources* 170, no.
25 2 (July 2007): 401–11. doi:10.1016/j.jpowsour.2007.04.036.
26 (8) Ercan, Tolga, and Omer Tatari. “A Hybrid Life Cycle Assessment of Public
27 Transportation Buses with Alternative Fuel Options.” *The International Journal of*
28 *Life Cycle Assessment* 20, no. 9 (September 2015): 1213–31. doi:10.1007/s11367-
29 015-0927-2.
30 (9) Cooney, Greg, Troy R. Hawkins, and Joe Marriott. “Life Cycle Assessment of Diesel
31 and Electric Public Transportation Buses: LCA of Diesel and Electric Buses.” *Journal*
32 *of Industrial Ecology*, April 2013, n/a – n/a. doi:10.1111/jiec.12024.
33 (10) Xu, Yanzhi, Franklin E. Gbologah, Dong-Yeon Lee, Haobing Liu, Michael O.
34 Rodgers, and Randall L. Guensler. “Assessment of Alternative Fuel and Powertrain
35 Transit Bus Options Using Real-World Operations Data: Life-Cycle Fuel and
36 Emissions Modeling.” *Applied Energy* 154 (September 2015): 143–59.
37 doi:10.1016/j.apenergy.2015.04.112.
38 (11) Spielmann, Mmichael, Christian Bauer, and Roberto Dones. “Transport
39 Services: Ecoinvent Report No. 14.” *EcoInvent Report*. Dübendorf: Swiss Centre for
40 Life Cycle Inventories, 2007.
41 (12) Chester, Mikhail, and Arpad Horvath. “Environmental Life-Cycle Assessment
42 of Passenger Transportation: A Detailed Methodology for Energy, Greenhouse Gas
43 and Criteria Pollutant Inventories of Automobiles, Buses, Light Rail, Heavy Rail and
44 Air v.2.” UC Berkeley Center for Future Urban Transport: A Volvo Center of
45 Excellence, March 1, 2008. <http://escholarship.org/uc/item/5670921q#page-1>.
46 (13) Tuchschnid, Matthias. “SBB Ecocalculator - Background Report.” Zurich,
47 October 2011.
48 (14) Chester, Mikhail, William Eisenstein, Stephanie Pincetl, Zoe Elizabeth, Juan
49 Matute, and Paul Bunje. “Environmental Life-Cycle Assessment of Los Angeles
Metro’s Orange Bus Rapid Transit and Gold Light Rail Transit Lines.” (Arizona State
University Report No. SSEBE-CESEM-2012-WPS-003) (Tempe, AZ: Arizona State

- 1 University), 2012. [https://repository.asu.edu/attachments/94226/content/chester-ASU-](https://repository.asu.edu/attachments/94226/content/chester-ASU-SSEBE-CESEM-2012-WPS-003.pdf)
2 [SSEBE-CESEM-2012-WPS-003.pdf](https://repository.asu.edu/attachments/94226/content/chester-ASU-SSEBE-CESEM-2012-WPS-003.pdf).
- 3 (15) “ISO 14040:2006 - Environmental Management—Life Cycle Assessment—
4 Principles and Framework.” International Organization for Standardization, 2006.
- 5 (16) “ISO 14044:2006 - Environmental Management—Life Cycle Assessment—
6 Requirements and Guidelines.” International Organization for Standardization, 2006.
- 7 (17) Jolliet, Olivier, Myriam Saadé-Sbeith, Shanna Shaked, Alexandre Jolliet, and
8 Pierre Crettaz. *Environmental Life Cycle Assessment*. Boca Raton: CRC Press, Taylor
9 & Francis Group, 2016.
- 10 (18) INSEE. “Territoire - Panorama - Martinique.” Accessed August 1, 2016.
11 http://www.insee.fr/fr/themes/document.asp?reg_id=23&ref_id=23559#inter3.
- 12 (19) “Rapport D’exploitation EMD Martinique 2013-2014.” ADUM, City and
13 Regional planning agency of Martinique, 2014.
14 [http://www.aduam.com/echanges/Rapport-exploitation-](http://www.aduam.com/echanges/Rapport-exploitation-EMD/Rapport%20d'exploitation%20EMD%202013-2014.pd)
15 [EMD/Rapport%20d’exploitation%20EMD%202013-2014.pd](http://www.aduam.com/echanges/Rapport-exploitation-EMD/Rapport%20d'exploitation%20EMD%202013-2014.pd).
- 16 (20) “Transports et Déplacements En Martinique.” Regard Croisé. ADUM, City and
17 Regional planning agency of Martinique, n.d. 2013.
- 18 (21) De Bortoli, Anne, Adélaïde Féraïlle, and Fabien Leurent. “Life Cycle
19 Assessment of the Environmental Performance of Urban Transportation Modes:
20 Integrated Methodology with Application to Bus Rapid Transit.” Hamburg, Germany,
21 2016. <http://dx.doi.org/10.5445/IR/1000051699>.
- 22 (22) Li, Bingbing, Jianyang Li, and Chris Yuan. “Life Cycle Assessment of Lithium
23 Ion Batteries with Silicon Nanowire Anode for Electric Vehicles.” In Proceedings of
24 the International Symposium on Sustainable Systems and Technologies. Figshare,
25 2013. <http://dx.doi.org/10.6084/m9.figshare.805147>.
- 26 (23) Guderian, Robert. *Air Pollution by Photochemical Oxidants Formation,*
27 *Transport, Control, and Effects on Plants*. Berlin, Heidelberg: Springer Berlin
28 Heidelberg, 1985. <http://dx.doi.org/10.1007/978-3-642-70118-4>.
- 29 (24) Sillman, S. “Tropospheric Ozone and Photochemical Smog.” In *Treatise on*
30 *Geochemistry*, 415–37. Elsevier, 2014.
31 <http://linkinghub.elsevier.com/retrieve/pii/B9780080959757009116>.
- 32 (25) De Bortoli, Anne. “Eco-Concevoir L’entretien Routier : Contexte National et
33 Identification Des Enjeux Énergétiques Du Système Routier.” *Revue Générale Des*
34 *Routes et de l’Aménagement*, no. 920 (June 2014).
- 35 (26) Eckelman, Matthew J. “Life Cycle Assessment in Support of Sustainable
36 Transportation.” *Environmental Research Letters* 8, no. 2 (June 1, 2013): 021004.
37 doi:10.1088/1748-9326/8/2/021004.
- 38 (27) Chester, Mikhail, Stephanie Pincetl, Zoe Elizabeth, William Eisenstein, and
39 Juan Matute. “Infrastructure and Automobile Shifts: Positioning Transit to Reduce
40 Life-Cycle Environmental Impacts for Urban Sustainability Goals.” *Environmental*
41 *Research Letters* 8, no. 1 (March 1, 2013): 015041. doi:10.1088/1748-
42 9326/8/1/015041.
- 43 (28) De Bortoli, Anne. “Assessing Environmental Impacts of Road Projects : The
44 Recent Development of Specialized Eco-Comparators in France.” Seoul, North Korea:
45 World Road Association, 2015.
- 46 (29) Wang, Ting, In-Sung Lee, Alissa Kendall, John Harvey, Eul-Bum Lee, and
47 Changmo Kim. “Life Cycle Energy Consumption and GHG Emission from Pavement
48 Rehabilitation with Different Rolling Resistance.” *Journal of Cleaner Production* 33
49 (September 2012): 86–96. doi:10.1016/j.jclepro.2012.05.001.

- 1 (30) Chester, Mikhail, and Arpad Horvath. "Life-Cycle Assessment of High-Speed
2 Rail: The Case of California." *Environmental Research Letters* 5, no. 1 (January
3 2010): 014003. doi:10.1088/1748-9326/5/1/014003.
- 4 (31) Helmers, Eckard, Johannes Dietz, and Susanne Hartard. "Electric Car Life
5 Cycle Assessment Based on Real-World Mileage and the Electric Conversion
6 Scenario." *The International Journal of Life Cycle Assessment*, July 31, 2015.
7 doi:10.1007/s11367-015-0934-3.
- 8 (32) Cucurachi, Stefano, Reinout Heijungs, and Katrin Ohlau. "Towards a General
9 Framework for Including Noise Impacts in LCA." *The International Journal of Life
10 Cycle Assessment* 17, no. 4 (May 2012): 471–87. doi:10.1007/s11367-011-0377-4.
- 11 (33) Weidema, Bo, Miguel Brandao, and Massimo Pizzol. "The Use of Monetary
12 Valuation of Environmental Impacts in Life Cycle Assessment: State of the Art,
13 Strengths and Weaknesses." *ScoreLCA*, 2013.