

## Environmental performance of urban transit modes: a Life Cycle Assessment of the Bus Rapid Transit



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### Abstract

Motorized modes of transportation, whether car or plane, bus or train, play a major role in developed societies. As they essentially trade energy against distance and speed of travel, their share in the overall consumption of energy and materials is high, making the reduction of that share an important objective for sustainability. This calls for both the systematic evaluation of environmental performance and the eco-design of transit modes. This twofold objective is addressed in the paper, which applies a Life Cycle Assessment (LCA) methodology to a transit mode, encompassing both infrastructure and vehicle fleets. The methodology is applied to a case study of a Bus Rapid Transit (BRT) system in Martinique, a French Caribbean island. The results show the contributions of the project's subsystems and life cycle phases to its environmental impacts, as captured by a set of 13 indicators. Impacts are normalized per passenger-kilometer. Comparison with other modes demonstrates the influence of vehicle occupancy rates and therefore the relevance of demand estimates in ex-ante evaluation. Finally, a sensitivity analysis is conducted to underline the respective impacts of input parameters on environmental impacts and to assess the potential of eco-design for BRT modes.

**Keywords:** LCA; road transportation modes; eco-design; Bus Rapid Transit; environmental performance

### 1. Introduction

The transportation sector contributes significantly to human environmental pressures on the planet, pressures that bring with them a cortege of negative impacts. It is therefore important to seek a systemic reduction in these impacts. In particular mass transit, provided that vehicle occupancy rates are high, has less environmental impact than automobile transportation. This article presents an eco-assessment of a Bus Rapid Transit system conducted using a Life Cycle Assessment (LCA) method. The case study focuses on a dedicated public transport line in Martinique designed to reduce congestion on existing roads. This forking line, with a total length of 15 km, will link the center of Fort-de-France to the town of Lamentin and to the airport. It includes 16 stations and 2 interchange hubs, and will be serviced by 14 hybrid 24 meter long bi-articulated buses. The project is being conducted under a public-private partnership and Caraïbus will hold a 20 year operating license for the line. The line is currently set to open at the end of 2015.

## 2. Methodology

LCA is a method used to estimate the materials and energy flows – and the potential environmental impacts – of a product or service throughout its life cycle: extraction and processing of raw materials, production, use, maintenance and end-of-life processing. Our study is the first multi-criteria process LCA conducted on a BRT system: it presents the environmental balance of the line over an observation period of 28 years – corresponding to the infrastructure's structural design – for each subsystem and life cycle phase, and then per passenger-kilometer covered. Our model was produced using OpenLCA software and is based on the European EcolInvent inventories. A set of 13 indicators was chosen to cover the main current ecological priorities. The specific data come from industrial partners in the BRT project, and were combined with modelling assumptions for each of the subsystems, divided up as follows: earthworks, pavements, sidewalk curbs, sidewalks and platforms, green spaces, street furniture, buses and their electric batteries.

## 3. Results and Conclusion

In the study, we obtain the contributions to environmental impact of each subsystem, then of each part of the construction process. Three subsystems in particular contribute to most of the impact categories: the road section infrastructure, the buses and the fuel they consume. With regard to the infrastructure, the pavement production impacts most heavily on the indicators, with some 30% of the total primary energy consumption, of the use of nonrenewable resources, of solid and radioactive waste, and of ozone layer depletion. Next, the line's environmental impacts per passenger-kilometer and under 3 occupancy scenarios are compared with other competing transport modes using the generic EcolInvent inventories: globally, the BRT's impact is much lower. Finally, trivial sensitivity tests were carried out on 4 parameters. The variability is high for the lighting and fuel consumption. The article goes on to discuss the use of LCA as a decision-making tool in the transportation look right sphere and avenues for development are proposed.

Space for notes

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## Abstract

Motorized modes of transportation play a major role in developed societies. As they essentially trade energy against distance and speed of travel, their share in the overall consumption of energy and materials is high, making its reduction an important objective for sustainability. This calls for both the systematic evaluation of environmental performance and eco-design of transit modes. This twofold objective is addressed in the paper, which applies a Life Cycle Assessment (LCA) methodology to a transit mode, encompassing both infrastructure and vehicle fleets. The methodology is applied to a case study of a Bus Rapid Transit (BRT) system in Martinique. The results show the contributions of the project's subsystems and life cycle phases to its environmental impacts, on a set of 13 indicators. Impacts are normalized per passenger-kilometer. Comparison with other modes shows the influence of vehicle occupancy rates and therefore the relevance of demand estimates in ex-ante evaluation. Finally, a sensitivity analysis is conducted on four input parameters, to assess the potential of eco-design for BRT modes.

**Keywords:** LCA; road transportation modes; eco-design; Bus Rapid Transit; environmental performance

## 1. Introduction

### 1.1 Context and objective

The transportation sector is a significant contributor to environmental impacts: In 2010, it accounted for 14% of global greenhouse gas emissions [1], primarily from road transportation. In urban environments, however, the development of new infrastructures that increase passenger capacity through mass transit services, could reduce energy demand from transportation by around 40% over its current level by 2050. Among these infrastructures, one that attracts particular interest is the infrastructure required for Bus Rapid Transit (BRT) systems[1], as an alternative to the private car. The main characteristics of a BRT system are: high-frequency service and greater regularity; higher operating speeds than a traditional bus, with the allocation of a dedicated lane on most of the route and priority at intersections; easy access for people with reduced mobility (station platforms at the same level as the vehicle footbed) and high levels of on-board comfort (movement space, fittings); reliable passenger information. The objective of this study is to carry out an eco-assessment of the BRT transit mode on a specific case study in Martinique, and to compare its environmental impacts with those of other competing urban transit

modes. For this BRT mode, we will apply the Life Cycle Assessment method of environmental evaluation.

## **1.2 Presentation of the research topic**

Our case study is a dedicated-lane mass transit (BRT) line in Martinique, a French Caribbean island. This forking line will link the center of Fort-de-France - capital of the island - with the town of Lamentin ("Mahault" interchange hub) and with the airport ("Carrère" interchange hub). It will have 16 stations, 2 interchange hubs, 1 maintenance center (outside the scope of this study) and will be serviced by fourteen 24 meter long hybrid bi-articulated buses. The project will be carried out through a public-private partnership, under which the firm Caraïbus will have a 20 year operating license, and is due to open at the end of 2015. On weekdays, the service will be open from 5:30 am to 10 pm. In terms of service frequency, from 2017 it is expected to run every 6 minutes at peak times (6:30 am-8:30 am and 4 pm-6 pm) on the main trunk line, and once an hour at slack times (after 8 pm), with intermediate intervals of 12 and 30 minutes at other times.

## **2. Methodology**

### **2.1 LCA and transportation: scientific positioning**

Life Cycle Assessment (LCA) is a method whose general framework and guidelines are established in ISO standards 14 040 and 14 044 [2]. It is used to the potential environmental impacts, of a product or service in the course of its life cycle, related to a functional unit with a quantified and time dimension. Initially developed and formalized for manufactured products or for services, the method's application to the transportation sphere is more recent and has given rise to a number of studies and questions [3]. A number of authors [4][5][6] distinguish 3 types of LCA: (i) "Process LCA" which is the most detailed, and where the inventory is based on the processes (i.e. physical flows) included within the perimeter of the system being studied; (ii) environmental Input-Output (EIO) analysis, in which inputs and outputs are calculated on the basis of national input-output tables which link economic flows for each sector with their environmental impacts; and (iii) "Hybrid LCA" which provides the missing data needed to carry out a Process LCA using the EIO analysis. This third form has been much used in this sphere of road transportation in the USA. France does not have EIO tables.

The LCA of road infrastructures, an avenue opened up in 1996 [7] and punctuated by numerous studies ([8], [9], and [10] to cite only a few), is now a fairly well-defined field. The usage phase has only recently begun to be modeled ([11], [12], [6]). Numerous LCAs have also been carried out on the comparison of bus traction forces ([13], [14], [15], ...) or on a standard bus [16], based for example on EcoInvent Life Cycle Inventories (LCI). Similarly, the bus mode has been studied – excluding infrastructure – with the aim of assessing the environmental impact of the traction mode over the life cycle on the basis of the local electricity mix [17]. However, there seem to be no process LCAs for a "complete" BRT line, including infrastructure and vehicles. The study by Chester and Horvath [18] is a hybrid LCA which models an average American urban diesel bus transit mode running on shared roads, taken up by Dave (2010) to compare "average" urban modes in the United States against energy and climate change criteria [19]. Spielmann's study [20] forms the basis of the transportation mode processes in the EcoInvent database and is based on averaged data (Europe or Switzerland). Another study presents the carbon footprint of a BRT line in China using LCA, but it is difficult to understand where the data come from [21].

Our study presents a Process LCA for a BRT line in which the assessment perimeter is wider than in previous studies, and based on industrial data. Our contributions lie in the application of process LCA to a real complex system, together with the creation of associated macroprocesses: earthworks, dedicated pavement, etc.

## 2.2 Definition of objectives and of the system studied

The aim is to conduct a process LCA for the Martinique BRT line over an observation period of 28 years – corresponding to the infrastructure’s structural design – for each subsystem and life cycle phase, and then per passenger-kilometer traveled. The function studied is the carriage of passengers on the line, and the functional unit is “providing passenger transportation on the line for the 28 years of the license, with a 5% level of infrastructural risk at the end of that term”. We consider that infrastructure construction – see items in column 4 of Figure 1 – is entirely dedicated to the transportation function. Since the lifespan of a road infrastructure is difficult to establish, we chose a period of observation for which the required maintenance forecasts are precise. In order to relate the impacts to the quantity of service provided, we normalize this functional unit per passenger-kilometer ([19], [14], [16], [18], [20]), on the basis of several line use scenarios. The system studied and its precise perimeter are described in Figure 1 and Table 1. In the absence of data, maintenances of street furniture, green spaces and sidewalks were excluded.

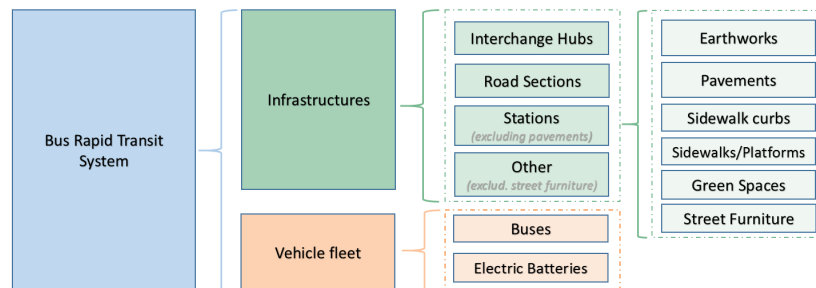


Figure 1 Description of the system studied: model per subsystem (column 3) and per construction batch (column 4)

Table 1 Life-cycle phases considered

<b>Subsystem</b>	<b>Construction</b>	<b>Use</b>	<b>Maintenance</b>	<b>End-of-life</b>	<b>Transportation</b>
Earthworks	X	///	X*	X*(100)	Included
Pavement	X	///	X	X*(>28)	Included
Sidewalk curbs	X	///	///	X*(>30)	Included
Sidewalks	X	///	///	X*(30)	Included
Green spaces	X	///	///	///	Included
Street furniture	X	X	///	X*(>28)	Included
Buses	X	X	///	X (14)	Europe to Martinique
Batteries	X	///	///	X (10)	Europe to Martinique

X\* (α)= not necessary over 28 years, lifespan considered = α

/// not applicable

A set of 13 indicators was chosen to cover the main current ecological priorities and the different natural compartments. Energy resource consumption was calculated by the Cumulative Energy Demand method. Solid and radioactive wastes were calculated by the EDIP method. The indicators on climate change, abiotic resource depletion, acidification, damage to the stratospheric ozone layer, photochemical oxidation, eutrophication, ecotoxicity and human toxicity are calculated by the CML 2001 method [22].

## 2.3 Sources of the life cycle inventory data

The data were provided by industrial partners in the BRT project. We chose to use the OpenLCA 1.3.1 open source software, because it allowed us to use the existing flows in EcoInvent or even to modify and adapt them. The EcoInvent database we used is the benchmark multi-topic

database for conducting a LCA in Europe. It contains international industrial data from life cycle inventories on energy supply, resource extraction, chemical products, metals, agriculture, waste management services and transportation services.

## 2.4 Assumptions

The quantitative estimates were made on the basis of the Caraibus partnership dossier, the Indicative Bill of Quantities provided by Eurovia, and documents from VanHool. We assumed building machines are used 7h/day, and its diesel consumption data are drawn from special databases (from SEVE and Gaïa, supplied by Eurovia), which take account of idle times. Depreciation on the building machines is not taken into account. The work rates are provided by Eurovia. The electricity mix chosen is, as a first approximation, that of Poland, which is very close to Martinique's, with some 95% coming from a thermal source. Unless otherwise stated, we exclude the transportation of materials before they reach the suppliers. The distances from supplier to site were either provided by our industrial partners, or calculated from the supplier list using Google Maps. For the road sections and stations, we take the barycenter of the total route as the starting point for calculating the distances from suppliers. Supplies are brought to the construction site in EURO4 standard 16-32 tonne trucks, except for the green spaces.

The fleet consists of fourteen 24 meter long bi-articulated buses, with a lifespan of 14 years. Because the percentage of unidentified materials in VanHool's data was too large relative to the cut-off threshold tolerated by standard NF P 01-010 (98%), we used EcoInvent's life-cycle inventories for bus construction, maintenance and end-of-life: we identified the materials and processing procedures relating to the thermal engine, then we carried out an initial LCA calculation proportional to the total masses of the VanHool bus and the EcoInvent bus, deducting the mass of their thermal engines (not proportional to the mass/size of the bus). We then complemented this with the process for the electric battery on the hybrid system ("*electric motor, electric vehicle, at plant, RER*"). From the mass of the battery, we calculated the mass ratio between the electric cells and the rest of the battery, drawing on the expert views of the French manufacturer Opel (which corroborate the data in the study by Li et al. [23]), and drew on the literature for data on the battery materials other than the electric cells [23]. We assumed the batteries to have a lifespan of 10 years, thus giving us 3 sets of batteries per bus, but 2 ends of life for our 28 year period of observation. With regard to bus usage, we considered two phases: a commissioning phase from 2015 to 2017 with 56 trips per day, then traffic growth of 0.42% per year over 26 years with, in 2018, 69 runs on the common trunk of the line in each direction and on each day, together with consumption measured on a SORT cycle of 56L/100 km. We adapted the "*operation, regular bus, CH*" process to the consumption and emissions (for NO<sub>x</sub>, CO<sub>2</sub> and CO) of the VanHool bus, measured by the World Harmonized Stationary Cycle procedure.

Of the line's total 15 km, 12.5 km were already built. Eurovia is building the remaining 2.5 km, as well as all the stations. We considered in our study that the 15 km were built and maintained in accordance with Eurovia's technical choices. The volumes of materials in the concrete components were calculated from standardised product sheets. The scaling and maintenance assumptions were provided by Eurovia. The factors systematically ignored are the different elements not quantified in the indicative BOQ, and small equipment that can be reused.

The "street furniture" item includes the production of the equipment, its transportation, and the energy consumed by the streetlamps and access barriers. When no specific data was provided, we chose the standard elements from supplier catalogs, conducted a materials assessment and selected the most appropriate EcoInvent processes, as far as possible including manufacturing processes. For the lighting, the batch consists of 1 streetlamp every 250 meters in each direction on road sections, switch cabinets, electric cabling and station lamps. For each station platform, this category includes a bus shelter, 4 benches, a CCTV pole, 2 trash cans, a switch cabinet, lighting and railings. Each interchange hub has 10 cycle racks, barriers, and 10 tree and streetlamp protection hoops. The materials assessment for the streetlamps was based on the catalog of the supplier Alunox, the assessment for the LED lamps (stations and hubs) and for the ONYX bulb lamps from the Eclatec catalog (road sections) using CEGELEC data, and the assessment of the switch cabinets on the basis of the Environmental Product Profile for Schneider Electric's Prisma Plus cabinet. The materials assessment for the bus shelters is extrapolated from the Techni-contact catalog. Each lamp operates for 4500 hours a year, with wattage of 50W for

the LEDs and 250W for the ONYX lamps. The total consumption of the automatic barriers is 15,000 kWh. Finally, it is assumed that all except the concrete elements are made in France at Clamart. They are shipped by road to the Port of Le Havre, then by boat to Martinique. In the green spaces category, we included the laying of the topsoil, the plantings and their street furniture, separators, painted markings... The concrete crash barriers are supplied by SATRAP, The crash barriers by GETELEC, the signage equipment and by SERR. The planting spoils are transported 20 km and the topsoil 25 km. Each tree planted weighs 200 kg, the turf is supplied in rolls (6 kg/m<sup>2</sup>). In the green spaces, trash cans, cycle racks, and streetlamps are made of steel.

### 3. Results

#### 3.1 Global results per subsystem

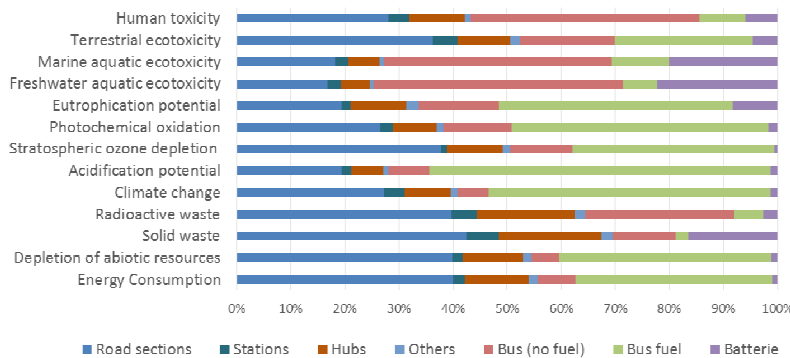


Figure 2 Contribution of each subsystem to the different impact categories

Figure 2 shows the contributions of each subsystem's environmental impacts. The "other" category covers the traffic circle and emergency exits. Three subsystems contribute particularly to the majority of the impact categories: the road sections, the buses and the fuel they consume. The electric batteries in the hybrid bus system also make a significant contribution to the impacts, with 16% for the solid waste indicator – linked with the current difficulty of recycling batteries – and respectively 22% and 20% for marine and freshwater aquatic ecotoxicities.

#### 3.2 Results per item group

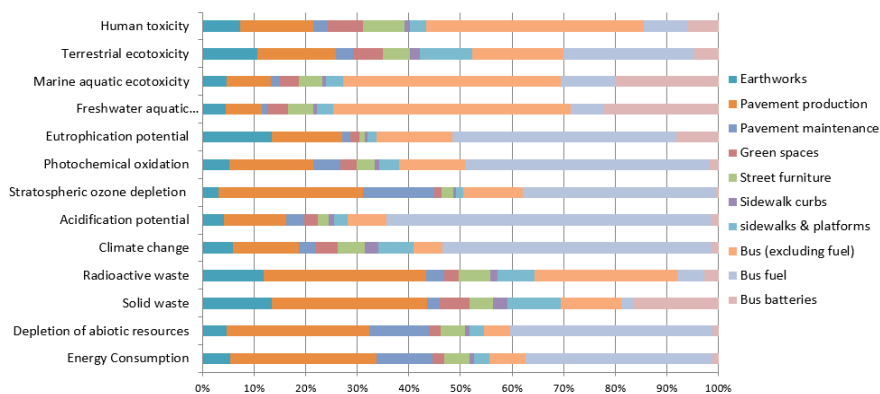


Figure 3 Contribution of each subsystem to the different impact categories

Alongside Figure 2 , Figure 3 shows the respective contributions of the street furniture, the green spaces and the phases of earthworks, pavement production and maintenance, sidewalks and

platforms. The impacts of the “green spaces” and “street furniture” item groups are low (never exceeding 8%). In terms of infrastructure, pavement production generates the greatest impact – some 30% of energy consumption, of the depletion of abiotic resources, of wastes, and of ozone layer destruction. Nevertheless, pavement maintenance is not insignificant, since in terms of energy consumption and resource depletion, it represents more than 10% of the impact sources.

### 3.3 Focus on the vehicles

Figure 4 shows the contributions of each phase in the life cycle of the bus, with a separate category for batteries. It is noteworthy that the production of the buses, their energy consumption during the usage phase, and the production of the batteries are the three items that account for most of the environmental impacts. While the impacts of the batteries are very low – less than 5% – in terms of photochemical oxidation, stratospheric ozone depletion, acidification and climate change, they nevertheless generate a significant proportion of the bus line’s (eco)toxicity effects (between 10 and 30%), as well as 53% of the solid waste. The fuel consumption item accounts for 82% of primary energy consumption, 86% of natural resource depletion, and also seems to be preponderant in the indicators for eutrophication (65%), photochemical oxidation (77%) stratospheric ozone depletion (76%), acidification (88%) and climate change (88%). Bus production has a particularly high impact on human toxicity (70%), and on freshwater (56%) and marine (52%) aquatic ecotoxicity. The environmental impacts of bus maintenance are generally low, with the exception of radioactive waste production, in which it accounts for 60% of the effects.

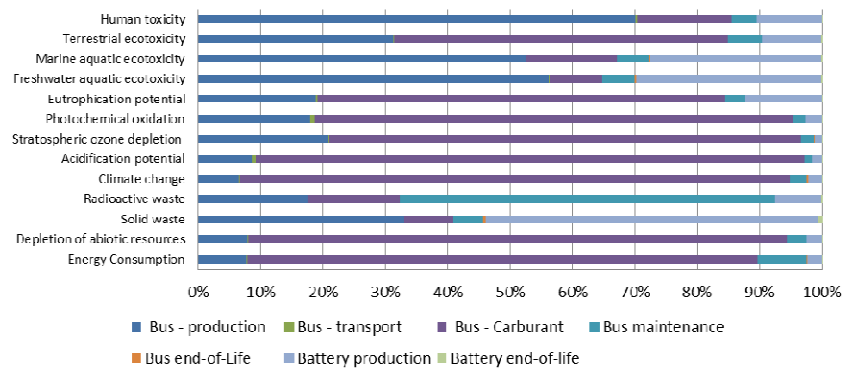


Figure 4 Contribution of each phase in the life cycle of the bus and its electric batteries

### 3.4 Focus on street furniture

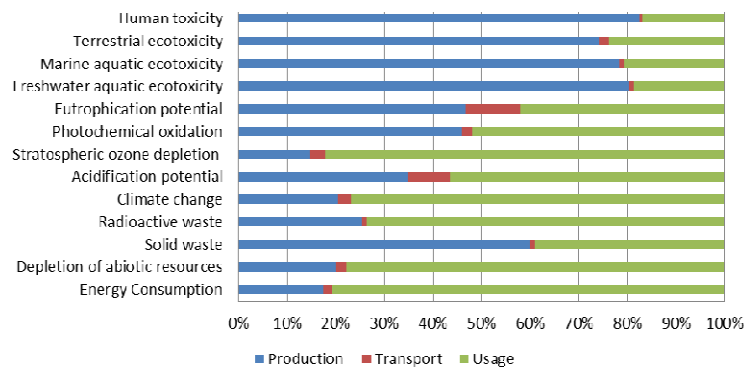


Figure 5 Contribution of each street furniture life-cycle phase to the different categories of impacts  
 Figure 5 identifies the contribution to environmental impacts of each life-cycle phase of the street furniture. The use phase, e.g. consumption from lighting, is preponderant on many indicators.

### 3.5 Normalization based on level of use, and multimodal comparison

Table 2 Environmental impacts of the line normalized per passenger-kilometer over an observation period of 28 years based on the average occupancy rate.

<i>Impact category</i>	<i>Impact/pkm with average occupancy rate (%)</i>			<i>Unit</i>
	<b>82%</b>	<b>50%</b>	<b>30%</b>	
Energy consumption	4.66E-01	7.64E-01	1.27E+00	MJ eq
Climate change at 100 years	2.23E-02	3.66E-02	6.10E-02	Kg CO2 eq
Depletion of abiotic resources	1.89E-04	3.10E-04	5.16E-04	Kg Eq antimony
Solid waste	2.04E-03	3.35E-03	5.59E-03	kg
Radioactive waste	5.86E-07	9.62E-07	1.60E-06	kg
Acidification potential – generic	1.47E-04	2.42E-04	4.03E-04	Kg SO2 eq
Stratospheric ozone depletion	4.68E-09	7.67E-09	1.28E-08	KgCFC11 eq
Photochemical oxidation	4.99E-06	8.18E-06	1.36E-05	kgEthyleneEq
Eutrophication – generic	3.93E-05	6.45E-05	1.07E-04	kg PO4 <sup>3-</sup> eq
Freshwater aquatic ecotoxicity at 100 years	3.66E-03	6.00E-03	1.00E-02	kg1.4DCBeq
Marine aquatic ecotoxicity at 100 years	1.46E-02	2.39E-02	3.99E-02	kg1.4DCBeq
Terrestrial ecotoxicity at 100 years	5.30E-06	8.70E-06	1.45E-05	kg1.4DCBeq
Human toxicity at 100 years	8.83E-03	1.45E-02	2.41E-02	kg1.4DCBeq

We performed a normalization of the impacts per passenger kilometer, under three scenarios: optimistic, moderate and pessimistic. As Table 2 shows, for the optimistic scenario, each passenger-kilometer would require an average energy consumption of 0.76 MJeq and would have an impact on climate change of 37 gCO<sub>2</sub>eq. In order to provide factors of comparison with the transport modes previously used on the route covered by the BRT line, these impacts could be compared with those of other modes. In the absence of spatialized data, as an example, we compare them by analyzing the EcoInvent processes corresponding to different competing modes with fixed occupancy. The levels of impact of the Martinique BRT in terms of energy consumption and climate change per passenger-kilometer, even in the case of the pessimistic scenario, are around 3 times lower than that of the private car (3.34 MJeq and 0.197 kgCO<sub>2</sub>eq) in European conditions, lower (respectively by 25 and 60%) than the standard bus (1.67 MJeq and 0.104 kgCO<sub>2</sub>eq) and slightly lower than the trolleybus mode in Swiss conditions in respect of energy consumption, but more than 2 times higher in terms of climate impact, and higher than the tramway. However, the BRT mode can only compete in terms of capacity with the tramway if the BRT has a high occupancy rate: with an average occupancy scenario, the BRT achieves 45% less energy consumption per passenger-kilometer, and lower consumption and emissions (respectively 60% and 25% less) under the optimistic occupancy scenario.

### 3.6 Sensitivity tests

We have just shown how sensitive the environmental impacts of the service provided by the BRT are to the average occupancy rates of the buses. However, the model's results are sensitive to many other parameters: to the expected lifespans of the subsystems, to the fuel consumption of the buses, to lighting... We conducted a number of trivial sensitivity analyses in order to quantify this roughly. First, our model allocates to the BRT the impacts of a streetlamp every 250 m in addition to the station lighting. In reality, the dedicated lane runs alongside existing mixed traffic lanes which also require lighting (one street lamp every 25 m). Under this hypothesis, its impacts would be much greater, between 3% and 20% depending on the indicator studied. The assumption regarding the bus's consumption is also important to the accuracy of the results: if it is reduced from 56L/100km to 42L/100km (consumption of a similar transit system in the city of

Metz, France), the environmental impacts diminish by 10% on 2/3 of the indicators. On the other hand, increasing the use duration of the buses would only have a small impact on the total balance, as would the use of batteries lasting only 5 years instead of 10 – except on the solid waste production indicator and the aquatic ecotoxicity indicators (Table 3).

Table 3 Variation in the impacts per passenger-kilometer relative to the base model

<b>Scenario</b>	<b>Base</b>	<b>Streetlamp /50 m</b>	<b>Bus used 18 years</b>	<b>Batteries used 5 years</b>	<b>Cons. 42L</b>
Energy	1	+16%	-0.39%	+1.1%	-9.0%
Abiotic resources	1	+15%	-0.16%	+1.1%	-9.8%
Solid waste	1	+13%	-0.23%	+16.5%	-0.6%
Radioactive waste	1	+19%	-2.37%	+2.7%	-1.3%
Climate change	1	+17%	-0.24%	+1.3%	-13%
Acidification potential	1	+6%	-0.10%	+1.3%	-16%
Stratospheric ozone depletion	1	+7%	-0.12%	+0.6%	-9.3%
Photochemical oxidation	1	+10%	-0.14%	+1.7%	-12%
Eutrophication potential	1	+3%	-0.24%	+8.2%	-11%
Freshwater aquatic ecotoxicity	1	+13%	-0.56%	+22.2%	-1.6%
Marine aquatic ecotoxicity	1	+12%	-0.53%	+20.0%	-2.6%
Terrestrial ecotoxicity	1	+15%	-0.29%	+4.7%	-6.3%
Human toxicity	1	+20%	-0.25%	+5.9%	-2.1%

## 4. Discussion

### 4.1 Scope of our results

We draw up an environmental assessment of the BRT mode on the entire life-cycle of the project. The asset of using LCA is to identify impact hotspots in order to improve the ecological performance of the mode. The elements with the greatest impact are the road sections, the buses and the fuel they consume. With regard to the infrastructure, the pavement contributes the most to the impacts measured by the indicators: around 25% of total primary energy consumption, depletion of abiotic resources, and solid waste, amongst other impacts. With regard to the street furniture, the largest share of the impacts comes in the use phase (through consumption from lighting). Normalization of the impacts and their comparison with other transit modes show that in a comparative approach, the environmental balance of a transportation project greatly depends on its success with user populations. Despite uncertainties, this study addresses the question of eco-designing a BRT mode. Given the importance of the pavement construction, it would be interesting to understand which processes have the greatest impact, so that they can be optimized. Similarly, consumption associated with lighting plays a not insignificant role, suggesting the possibility of improvements to the bulbs used.

### 4.2 Current limitations of LCA as a decision-making tool in the transportation sphere

The limitations of this study are primarily those of LCA as a decision support tool: restricted to a set of ecological indicators, omitting local indicators (landscape, noise, odors...); its implementation entails uncertainties; its results obviously depend on the choice of the boundaries and the hypotheses, and vary depending on the degree of specificity of the model (e.g. via spatialization of the data). Next, the limitations are linked specifically with our working hypotheses: the choice of a period of observation, the definition of the system and its development over 28

years. On the latter point, the assessment is retrospective on construction, but prospective on system operation: traffic levels, system's real maintenance and consumption needs are uncertain. Numerous questions arise from this study. First, what is the feasibility of this kind of process LCA for the stakeholders associated with a transportation project? The current cumbersome nature of the processing, combined with the very high need for data, cause problems for a systematic analysis. The EIO method reduces the time needed for conducting environmental assessments, while maintaining a wide assessment scope, but can only be used to conduct an assessment on average over the territory covered by the input-output matrices. Then, how to coordinate the implementation of the LCA? The need for very detailed data in a process LCA demands the involvement of numerous actors: manufacturers, designers, subcontractors, etc. Finally, at what point should a LCA be conducted? A ex-post LCA is more precise than a prospective one, but at that point it is too late to optimize most of the choices about the transportation project. As LCA is rather a comparative tool, it would have been more relevant to use it on technical variants. Nevertheless, we did not get such data.

## 5. In conclusion: our recommendations for broadening the scope

In current conditions, the existing life cycle inventories can be used to compare the environmental performance of transit modes on a wide scale like that of a country. LCA-based tools can thus be used by mass transit passengers to compare several routes from an environmental point of view [24], or else by companies to calculate the environmental impacts caused by the traffic they generate [25]. Nonetheless, there exists no tool to guide investment in transit systems or to optimize transit systems in a global manner. One possible avenue of implementation in public policies would be to produce more spatialized inventories associated with transit projects and to insert them into a multimode LCA transportation tool, with a user-friendly interface and a number of default data, which could be modified by the user to represent specific cases. This would facilitate faster implementation of LCA studies by both clients and contractors. It seems important that the results should include an estimate of uncertainties and variability, depending on the input and for each indicator, as shown by our handful of sensitivity tests – at least for use in “expert” mode if the software offers several levels of use. The prospective dimension of the tool would also seem to be a crucial advantage when seeking to rationalize a technical choice relating to objects with long lifespans, whose characteristics and therefore environmental impacts are likely to change over time. Such an instrument would enable decision-makers to assess the environmental dimension of the planning and operation of their transit system against a range of selected criteria. It would also be interesting to be able to incorporate the social and economic dimensions into a more global assessment tool, not solely restricted to the LCA methodology.

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