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# Case study: Bike sharing

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## Outline

## 1 Introduction

Bike-sharing services make bicycle available for shared use or rent on a short-term basis, usually, urban contexts. The users pay for the service through computers or apps. In the last decade, thanks to improvements in technology, bike sharing has experienced a significant diffusion being present in more the 2,000 cities worldwide [1, 2].

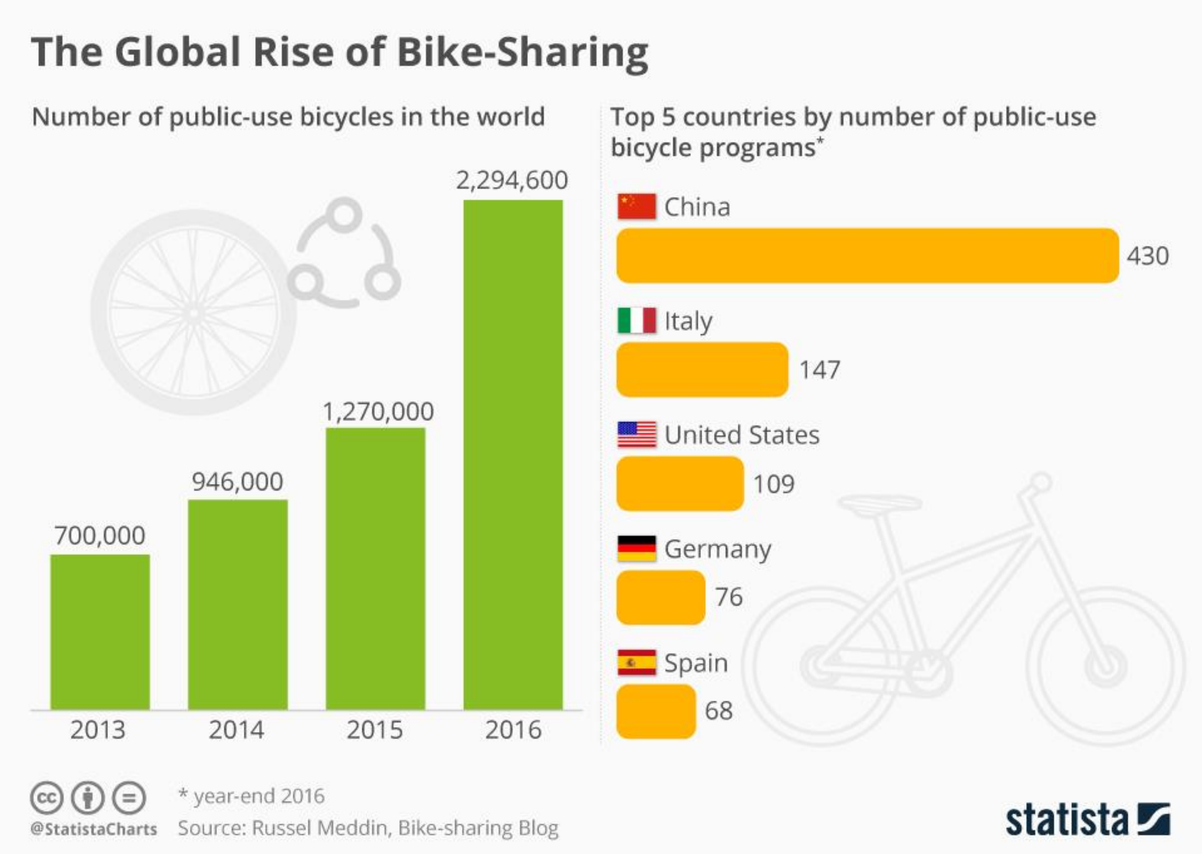


*Figure 1. The rise of bike-sharing (SOURCE:https://www.statista.com/chart/13483/bike-sharing-programs/)*

Under a global perspective, Europe [3] has been a frontrunner in the implementation of bike-sharing services and so is Germany (Figure 1): in its capital, Berlin, there exist different bike providers, such as Byke, Donkey Republic, Lidl bikes, Lime bike, Mobike, Nextbike, Obike and Ofo [4], and the number of bike-sharing bikes available is constantly increasing (Figure 2).

The bike-sharing services are said to make urban cycling more accessible, popular, and smart, to contribute to the development of urban cycling infrastructures [5]. On the environmental side, increases in bike travels can contribute to reduce urban air pollution and greenhouse gas emissions: according to WWF China, the only Mobike users, after one year of service, have collectively cycled over 5.6 billion kilometers, equivalent to reducing $CO_2$ emissions by more than 1.26 million tons, or taking 350,000 cars off the road for a year [6].

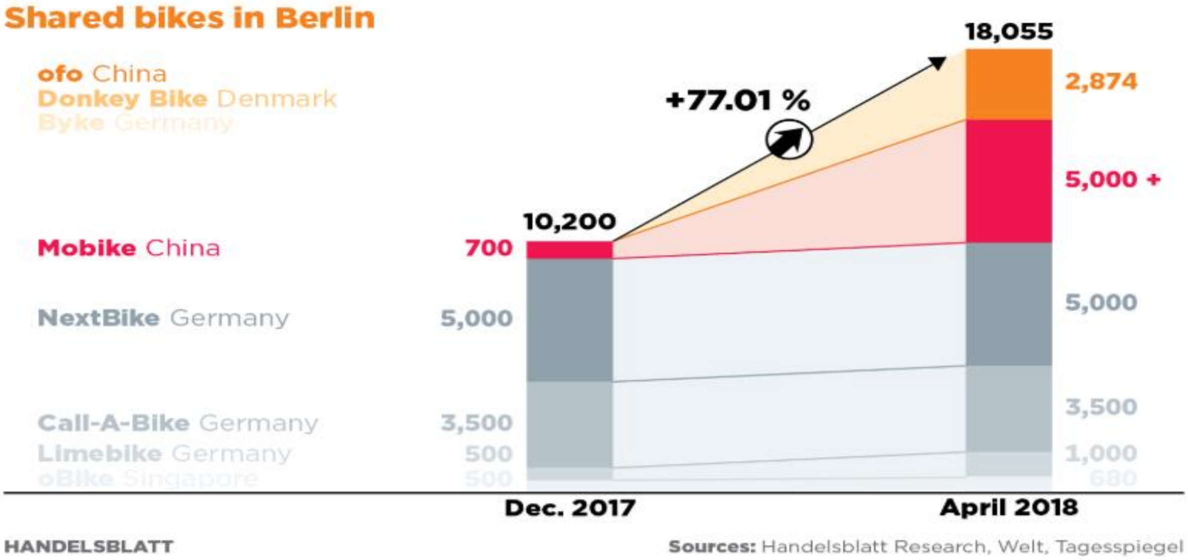


*Figure 2. Bike-sharing bikes in Berlin*

On the other hand, existing bike-sharing services have been facing issues related to bikers' safety [7], damages to the traditional bike industry [8], and most of all to the high breaking and abandonment rates and difficult maintenance activities (e.g., defining strategies to reduce the effort like using rubber-filled wheels instead of air-filled ones) [9]. These two latter issues can affect the environmental benefits brought by the bike-sharing service, since they cause additional use of material and energy (i.e., to substitute the broken bikes or components).
Given this controversial influence on the environment, this study aims to assess the environmental impacts of the bike sharing service considering the whole life cycle of the bicycles, from the raw material production, through their use phase, to the waste disposal, through the Life Cycle Assessment methodology. We aim to answer the following research questions:

1. Which are the environmental impacts of a bike-sharing bike along its whole life cycle?
2. Which are the contributions of the different life cycle stages? And the main causes of impact within each life cycle stage?
3. How do bike weight, material composition, production site, lifespan and risk of damage affect the environmental performance of the bike sharing bikes?
4. Among the available urban transportation means, how is bike sharing performing under an environmental perspective? How is the comparison affected by the assumption on the average lifespan of vehicles?

## 2 Goal and scope definition

To study the environmental impacts of bike-sharing bike we adopt a cradle-to-grave approach, covering the bike production, the use-phase and the end-of-life (Figure 3). We focus on the so-called smart bikes, i.e., those bike-sharing bikes that do not need dock station and include all the technological components required to manage the service. For this reason, the doc stations involved in some bike sharing systems are instead excluded from the analysis.

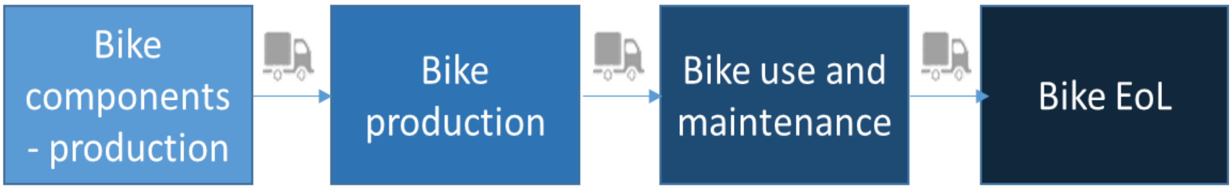


*Figure 3. Bike-sharing bike life cycle under study*

The functional unit (FU) adopted to assess the environmental impacts of bike-sharing bike is 1-person kilometer (1 p*km), namely 1 kilometer travelled by 1 person.

## 3 Inventory analysis – baseline and alternatives

This section is dedicated to the description of the data used in this study. We used only secondary data provided by the database ecoinvent 3.4. The life cycle of a bike is divided into three major phases: (i) bike production (section 3.1), (ii) bike use (section 3.2) and end-of-life or disposal of the bike (section 3.1). In section 3.3, we present the alternative cases built on variation of the main assumptions adopted in the baseline case.

### 3.1 Bike production

The dataset used as a baseline case for this case study is named "*bicycle production | bicycle | Cutoff, U, RoW* (based on "bicycle production, RER 2009"). The data set reflects a bike of 17kg with an aluminum frame and including additional equipment (e.g. carriers, lights). It covers the energy and materials used for the manufacturing of the bike and the final disposal. The manufacturing of the bike parts is assumed to take place in China, as the majority of bike sharing bikes [10]. Transport to Europe included[1]. The disposal is modelled considering global average conditions ('*market for used bicycle | used bicycle | Cutoff, U'* e.g., rubber is incinerated, plastic is both incinerated, used for clinker production and disposed in landfill).
The materials composing the bike are summarized in Table 1. More than 80% of the bike weight is due to metals (i.e., steel and aluminum), while the rest is mainly plastics and rubber (Figure 4).

*Table 1. Bike material composition*

| Materials | Amount (kg) | COMPOSITION |
|---|---|---|
| polyethylene, high density, granulate | 2.0 | 11.6% |
| polyurethane, flexible foam | 0.3[2] | 1.8% |
| synthetic rubber | 0.6 | 3.3% |
| steel, chromium steel 18/8, hot rolled | 1.6 | 9.4% |
| steel, low-alloyed, hot rolled | 4.9 | 28.9% |
| Aluminum, wrought alloy | 7.5 | 44.5% |
| coating powder | 0.1 | 0.6% |

[1] Being produced in Far East Asia, shipping of the components to the final assembly site in Europe is taken into account. Long distance transport is usually carried out by oceanic freight ships (13'000 km) whereas the distribution in Europe is carried out by lorries with more than 16 tons cargo weight (1000 km).
[2] The value in the original DB is 0.03 kg, but since this material represents the bike saddle, it is more likely to be 300 g

| TOTAL | 17.0 | 100% |
|---|---|---|

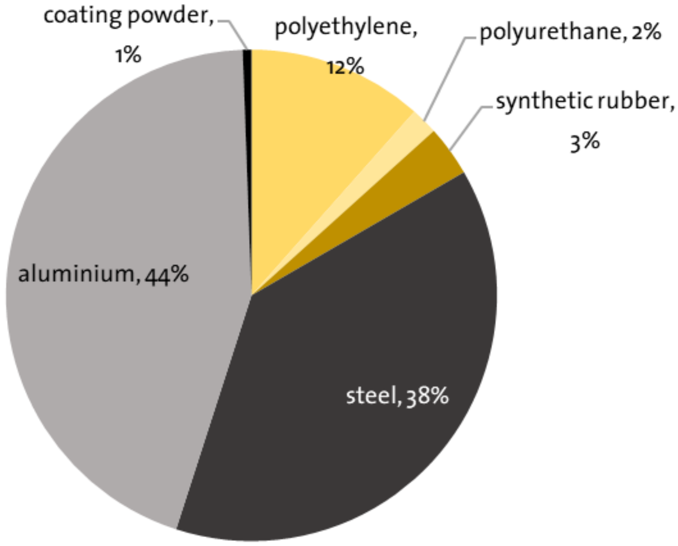


*Figure 4. 17-kg bike material break-down*

## 3.2 Bike use phase and maintenance

The use phase of a bike includes the (i) maintenance of the vehicle (e.g., components substitution) and (ii) road construction, renewal and disposal. A crucial element characterizing the use phase of a bike is the assumption on its lifespan. This is usually expressed in terms of kilometers and it is necessary to define the maintenance activities and to allocate the impacts of the production to each single travelled km, and consequently allowing comparison with other transportation means. In the used dataset (ecoinvent 3.4), the lifespan of a bike is assumed equal to 15,000 km. Concerning the maintenance, the data set used (i.e., *maintenance, bicycle / maintenance, bicycle / Cutoff, U*) considers the replacement of bike components following the assumption reported in Table 2. The considered datasets have been developed to describe a private bike but given the lack of primary data and some similarities (e.g., average weight), we use them to describe the baseline scenario of a bike-sharing bike, and we test sensitive assumptions and data through the analysis of alternative cases.

*Table 2. Bike maintenance - assumptions adopted in the ecoinvent 3.4 dataset*

| MATERIAL SUBSTITUTION | ASSUMPTIONS |
|---|---|
| aluminum alloy, AlMg3 | 5% of aluminum parts replaced |
| polyurethane, flexible foam | saddle once replaced (HP. 300 g)[3] |
| steel, low-alloyed, hot rolled | 5% of steel parts replaced |
| synthetic rubber | 3.75 bike tire-sets use in life-time |
| polyethylene, high density, granulate | 50% of plastic parts once replaced |

[3] With respect to ecoinvent, the input flow has been increased up to 300 g (from 30 g).

Besides the lifespan of a bike and its maintenance, the road infrastructure contributes to environmental impacts of the bike use phase. The considered dataset (*road construction | road | Cutoff, U*) represents the expenditures and interventions due to the provision of road, tunnel and bridge infrastructures, the renewal of different road layers and eventual road disposal.[4] All environmental exchanges refer to one meter and year (m*a): the specific road demand for a vehicle is assumed to be directly related to gross vehicle weight (i.e., vehicle plus load) and the overall presence of this type of vehicle (expressed in km year$^{-1}$) on a given road network [11]. In the case of the considered dataset, the model is based on Swiss motorways and roads [12, 13]. In the case of bicycles, as for small scooters, road maintenance and operations (e.g., snow clearance and pavement repair on motorways) is not considered [14].

## 3.3 Baseline and alternatives cases

The bike sharing market provides different alternatives, which vary in the type of bikes and service (e.g., costs, dock or dock-less). In this study, we focus on possible variations in environmental impacts due to the different types of bike-sharing bikes available on the market. Exploring the available information about the existing bike sharing alternatives, we identify three main weight categories that describe also the evolution of the bike sharing over the years Table 3).

*Table 3. Bike-sharing weight: 3 bicycle generations*

| ID | WEIGHT (kg) | BRAND EXAMPLE (production site) |
|---|---|---|
| Heavier-bike | 25 | -Mobike - 1st model (*China*) [15, 16, 17]<br>-Lidl-bike (*Germany*) [18] |
| Baseline | 17 | -Mobike – 2nd model (*China*) [19]<br>-Ofo (China) [20] |
| Lighter-bike | 15.5 | -Mobike – 3rd model (*China*) [21] |

Given these three categories, we will proceed according to two approaches:

1. The variation of weight is homogeneously spread on all the materials, proportionally to their amount in the baseline. Accordingly, since weight changes influence all the flows involved in the bike production (both materials and energy), we created a parameter describing the total bike weight, more precisely, it is defined as the ration between the weight selected for a specific bike and the weight assumed in the baseline scenario (i.e., 17 kg). All the involved flows have been then made dependent to this parameter, which influences the amount of materials and the manufacturing processes proportionally to the amount assumed in the baseline scenario (multiplicative parameter)[5]. This approach will be adopted also to test the sensitivity to weight of impacts due to bike use (i.e., both maintenance and road use).
2. The variation of weight is due to the variation of specific materials composing the bike. Bike-sharing bikes can include built-in locks, radio tracking device, a dropped down-tube (i.e. a

[4] The dataset starts with land transformation for the construction/replacement of roads. The dataset ends with the replacement of road, tunnel and bridge infrastructures. The dataset includes the land, material and energy uses and the construction processes (excavation). It also includes the NMVOC and particulate matter emissions, and the eventual disposal of the road infrastructures as a continuous process of renewal.

[5] Assumption: linear dependence of all the flows to the total bike weight

girly-style) frame, wide sprung seat, large flat-proof tires, racks and several reflectors [22, 23]. Since this study is based on secondary data and is not focusing on a specific model of bike-sharing bike, we test the sensitivity of environmental impacts towards the variation of the three main materials, whose cumulatively contribute to more than 80% of the total weight (i.e., 85%). We test the increase of 1 kg of these three main materials (and the related processes, Table 4). Despite the lack of specific data, we additionally test two more specific cases that are likely to happen in real bike-sharing bikes, according to the information found in the web: the presence of airless or flat-proof tires, and presence of bigger and wider saddle (Table 5). In this case we just modify the amount of material in the inventory, while we do not modify energetic and waste flows.

*Table 4. Alternative bike maintenance assumptions on substituted materials and relative processes*

| Materials | Fraction | Process | Material involved |
|---|---|---|---|
| polyethylene, high density, | 11.60% | injection molding | 100% |
| steel, low-alloyed, hot rolled | 28.90% | wire drawing | 7% |
| aluminum, wrought alloy | 44.50% | section bar extrusion | 50% |

*Table 5. Alternative bike maintenance assumptions on saddle and tires substitution*

| Materials | baseline (kg) | new HP (kg) | variation (%) |
|---|---|---|---|
| polyurethane, flexible foam | 0.3[6] | 1.05 [24] | +250% |
| synthetic rubber | 0.6 | 0.92 [25, 26] | +53% |
| **TOTAL** | **17.0** | | |

Besides, the variation of weight, we tested a different production site: instead of assuming China as the production site, we assume that the bike is produced in Europe. This is not the case in most bike-sharing bikes, but it happens for few options like the Lidl-bikes [27]. To test this alternative case, we use the dataset "*bicycle production | bicycle | Cutoff, U, RER*" provided by ecoinvent 3.4, in which energy (i.e., electricity and heat), water and wastewater are described with average European data.

Referring to the whole life of a bike-sharing bike, we then test the sensitivity of the results towards the assumption regarding the lifespan of a bicycle (in the baseline this is assumed equal to 15,000 km). In the case of bike-sharing bikes this is an important assumption, since one of the negative aspects of this service is the high rates of damage that reduce the life of the bikes with respect to private bikes.

Finally, relating to the increases in risk of damages, we test how increases in the materials substitution affect the environmental impacts of the bike sharing service (while instead maintaining the assumption on the lifespan of the entire bicycle equal to 15,000 km). The assessed cases are summarized in Table 6.

*Table 6. Alternative assumptions on the risk of bike breakage (i.e., increase in component substitution effort)*

| substituted | Substituted quantity | |
|---|---|---|
| component or | additional items / % of | g |

[6] The value in the original DB is 0.03 kg, but since this material represents the saddle, it is more likely to be 300 g instead of 30g

| material | material (vs baseline) | |
|---|---|---|
| Saddle | + 1 saddle | + 300 g |
| Tires | + 1 tire | + 450 g |
| Aluminum | + 1% | + 75 g |
| Steel | + 1% | +49 g |
| Polyethylene | + 1% | +20 g |

## 3.4 Urban (public) transportation means – comparison

As a final step of the bike-sharing bike assessment, we perform a comparison with other transportation means available in urban contexts (Table 7). As a first step, we compare the baseline scenarios of the considered transportation means, namely by maintaining assumptions such as the lifespan and the number of passengers as provided by the database. Secondly, we introduce a parameter to simulate the reduction in lifespan[7] proportional to the one assumed in the database (i.e., the parameter is defined in percentage terms) and compare again the transportation means.

*Table 7. Baseline assumptions on urban vehicle lifespan and average passengers (i.e., the reported values are the product of these two assumptions)*

| Transportation mean | (average) passengers*km travelled/vehicle (p*km) |
|---|---|
| bike-sharing bike | 1.50E+04 |
| bus | 1.40E+07 |
| e-bike | 1.50E+04 |
| scooter | 5.50E+04 |
| tram | 5.92E+07 |
| urban train (CH) | 9.29E+08 |

# 4 Summary of modelling approach and cases under study

The modelling approach adopted to assess the environmental impacts of the bike-sharing services is summarized in Figure 5: in grey the main components of the bike life-cycle stages are highlighted; the three diamond-shaped boxes in yellow represent the parameters defined to model the alternative cases; the yellowish dashed arrow represent the influence of those parameter on to the bike life cycle components.

[7] We assume no changes in the average number of passengers

Bike sharing

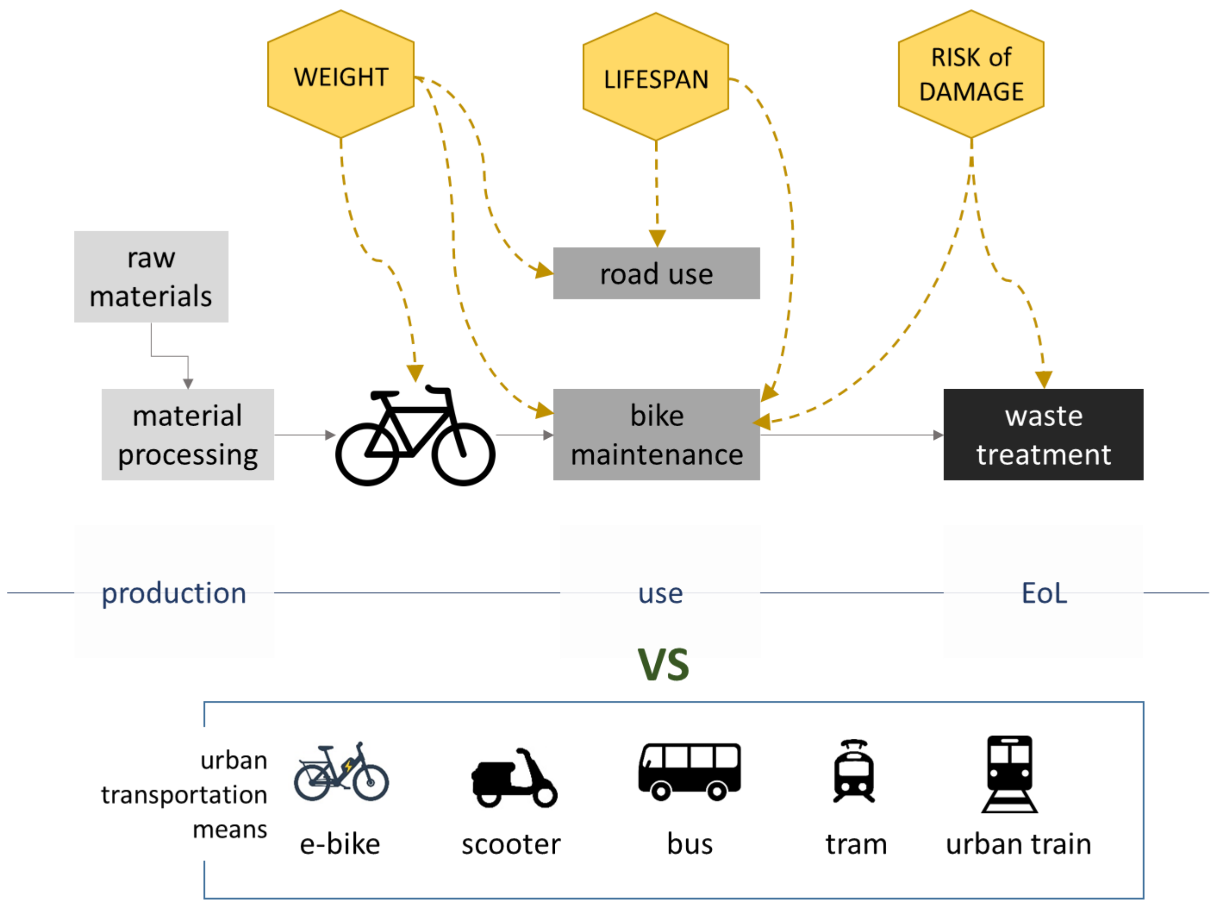


*Figure 5. Summary of the analysis carried out in this study*

In Table 8, we summarized the cases (baseline and alternatives) analyzed in this study and highlighted the main differences.

*Table 8. Summary of the cases analyzed in this study*

| Case | **Bike weight** | **Lifespan** | **Country of production** | **Substituted components** |
|---|---|---|---|---|
| **baseline** | 17 kg | 15,000 km | China | Table 2 |
| **weight - total** | 15.5 – 25 kg | = | = | = |
| **weigh - components** | Table 4 and 5 | = | = | change proportionally |
| **production location** | = | = | Europe | = |
| **lifespan** | = | 15,000 km → 15 km | = | change proportionally |
| **risk of damage** | = | = | = | Table 6 |

## 5 Life Cycle Impact Assessment method

The impact assessment method used in this study is called ReCiPe Midpoint (H) and it includes 18 environmental impact categories, which are summarized in Table 9.

*Table 9. ReCiPe Midpoint (H) - list of indicators and acronyms used in this study*

| **Impact category** | **ID** (acronym used in this study) | **Reference unit** |
|---|---|---|
| agricultural land occupation | ALO | $m^2a$ |
| climate change | CC | kg CO2-Eq |

| | | |
|---|---|---|
| fossil depletion | FD | kg oil-Eq |
| freshwater ecotoxicity | FETOX | kg 1,4-DCB-Eq |
| freshwater eutrophication | FEUT | kg P-Eq |
| human toxicity | HTOX | kg 1,4-DCB-Eq |
| ionizing radiation | IR | kg U235-Eq |
| marine ecotoxicity | METOX | kg 1,4-DCB-Eq |
| marine eutrophication | MEUT | kg N-Eq |
| metal depletion | MDP | kg Fe-Eq |
| natural land transformation | NLT | $m^2$ |
| ozone depletion | OD | kg CFC-11-Eq |
| particulate matter formation | PMF | kg PM10-Eq |
| photochemical oxidant formation | POF | kg NMVOC |
| terrestrial acidification | TA | kg SO2-Eq |
| terrestrial ecotoxicity | TETOX | kg 1,4-DCB-Eq |
| urban land occupation | ULO | $m^2a$ |
| water depletion | WD | $m^3$ |

# 6 Results

In this section, the results of the impact assessment are presented. The first analysis regards the baseline scenario defined for bike-sharing bikes (both overall impacts and break-down into the different life cycle steps; section 6.1). Secondly, we present the results obtained alternative cases summarized in Table 8 (section 6.2). Finally, we compare the bike-sharing service with other urban transportation means (section 6.3).

## 6.1 Bike sharing environmental impacts: production, use, EoL/disposal

The environmental impacts caused by the 1 p*km travelled (i.e., functional unit) with an average bike-sharing services causes under a life cycle perspective are reported in Table 10.

*Table 10. Life Cycle Impact Assessment of bike-sharing bike - baseline scenario*

| Impact category | ID | units | Impact |
|---|---|---|---|
| agricultural land occupation | ALO | m2a | 3.70E-04 |
| climate change | CC | kg CO2-Eq | 1.41E-02 |
| fossil depletion | FD | kg oil-Eq | 3.86E-03 |
| freshwater ecotoxicity | FETOX | kg 1,4-DCB-Eq | 4.10E-04 |
| freshwater eutrophication | FEUT | kg P-Eq | 4.92E-06 |
| human toxicity | HTOX | kg 1,4-DCB-Eq | 5.87E-03 |
| ionizing radiation | IR | kg U235-Eq | 6.00E-04 |
| marine ecotoxicity | METOX | kg 1,4-DCB-Eq | 3.80E-04 |
| marine eutrophication | MEUT | kg N-Eq | 1.47E-05 |
| metal depletion | MDP | kg Fe-Eq | 2.35E-03 |
| natural land transformation | NLT | m2 | 1.84E-06 |
| ozone depletion | OD | kg CFC-11-Eq | 6.77E-10 |
| particulate matter formation | PMF | kg PM10-Eq | 3.63E-05 |
| photochemical oxidant formation | POF | kg NMVOC | 4.67E-05 |

| | | | |
|---|---|---|---|
| terrestrial acidification | TA | kg SO2-Eq | 6.72E-05 |
| terrestrial ecotoxicity | TETOX | kg 1,4-DCB-Eq | 6.37E-07 |
| urban land occupation | ULO | m2a | 5.20E-04 |
| water depletion | WD | m3 | 3.82E-05 |

In Figure 6, the overall impacts are split into the three main life cycle steps: bike production and disposal, bike maintenance and road use. Bike production and disposal (represented with dashed light-blue bars) cause the highest fraction in all the impact categories considered (i.e., ranging between 20.86% and 91.15%), but for the urban land occupation category. The main causes are the use of metals, such as aluminum (contributing between 4% and 54% of this phase, for metal depletion and terrestrial acidification, respectively) and steel (contributing between 3% to 28%, for urban land occupation and metal depletion, respectively).

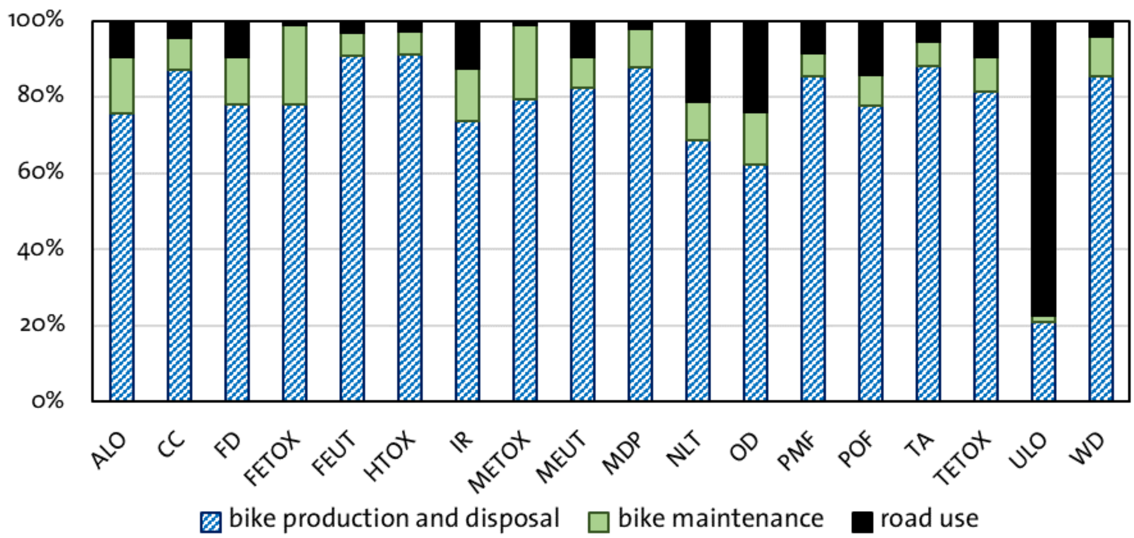


*Figure 6. Environmental impacts of bike-sharing - split into the main bike life cycle components*

The bike maintenance causes between 1.91% (urban land occupation) and 20.55% (freshwater ecotoxicity) of the impacts, depending on the category. The main causes are synthetic rubber for tire substitution (contributing between 4% and 65% of this phase, for metal depletion and terrestrial acidification, respectively) and substitution of aluminum components (contributing between 6% and 76% of this phase, for agricultural land occupation and freshwater ecotoxicity, respectively). Finally, the road use causes between 1.26% and 77.23% of the impacts, depending on the category. It is the major cause of impact for the category *urban land occupation*, due to urban area occupied by roads.

### *6.1.1 Bike production and disposal*

The production and disposal of bicycle emerged as the life cycle stage causing the highest impacts. In this paragraph, we focus on this life cycle step and identify the major caused of impacts (Figure 7). Materials cause the highest impacts in all the categories, with a contribution on total impacts ranging from 68.7% for Freshwater eco-toxicity and 99.4% for metal depletion. Among the used materials, aluminum and steel play key roles (both raw materials and related processes): aluminum shows an average contribution to 64.3%, ranging from 6.4% (metal depletion) to 83.14% (terrestrial acidification; steel shows an average contribution of about 22%, ranging from 9.7% (terrestrial acidification) to 92.5% (metal depletion). On the other hand, the disposal of a used bike contributes on average to 1.8% of the considered impact categories, with a peak of 8.48% in the fresh water ecotoxicity category and a negative impact (-0.14%) in the natural land transformation one.

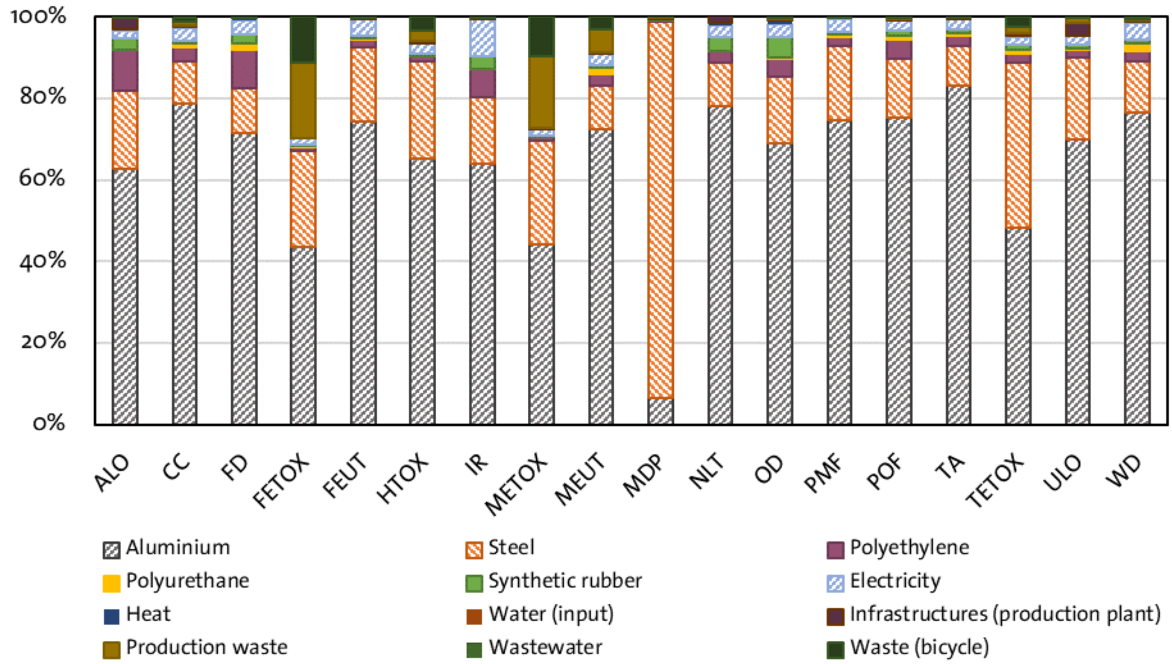


*Figure 7. Environmental impacts of bike-sharing production - split into the main components*

## 6.2 Alternative cases for bike-sharing service

### *6.2.1 Changes in bike weight – overall*

The change of the overall weight of the bike influences the environmental impacts caused by both the production, the maintenance of the bike and the use of road (Table 11). Overall, an increase in weight up to 25 kg (i.e., 47%) causes an increment ranging between 17% (urban land occupation) and 46% (metal depletion). While a reduction in weight of future bikes down to 15.5 kg reduced the impacts between -3% (urban land occupation) and -9% (metal depletion). The urban land occupation showed the lowest variations since it is mainly influenced by the bike occupation (in terms of number of bikes travelling on the considered road), while metal depletion showed the highest variation, since more than 80% of the bike weight is due to metals (i.e., alloy and steel).

*Table 11. Baseline vs. alternative bike weights, i.e., 25.5 kg (heavier) and 15.5 kg (lighter)*

| Impact cat. ID | units | baseline | heavier | lighter |
|---|---|---|---|---|
| ALO | m2a | 3.66E-04 | 5.24E-04 | 3.36E-04 |
| CC | kg CO2-Eq | 1.41E-02 | 2.05E-02 | 1.30E-02 |

| | | | | |
|---|---|---|---|---|
| FD | kg oil-Eq | 3.86E-03 | 5.54E-03 | 3.55E-03 |
| FETOX | kg 1,4-DCB-Eq | 4.09E-04 | 5.83E-04 | 3.76E-04 |
| FEUT | kg P-Eq | 4.92E-06 | 7.17E-06 | 4.50E-06 |
| HTOX | kg 1,4-DCB-Eq | 5.87E-03 | 8.49E-03 | 5.38E-03 |
| IR | kg U235-Eq | 6.02E-04 | 8.53E-04 | 5.55E-04 |
| METOX | kg 1,4-DCB-Eq | 3.78E-04 | 5.41E-04 | 3.48E-04 |
| MEUT | kg N-Eq | 1.47E-05 | 2.09E-05 | 1.35E-05 |
| MDP | kg Fe-Eq | 2.35E-03 | 3.43E-03 | 2.14E-03 |
| NLT | m2 | 1.84E-06 | 2.56E-06 | 1.70E-06 |
| OD | kg CFC-11-Eq | 6.77E-10 | 9.33E-10 | 6.29E-10 |
| PMF | kg PM10-Eq | 3.63E-05 | 5.21E-05 | 3.33E-05 |
| POF | kg NMVOC | 4.67E-05 | 6.61E-05 | 4.30E-05 |
| TA | kg SO2-Eq | 6.72E-05 | 9.73E-05 | 6.15E-05 |
| TETOX | kg 1,4-DCB-Eq | 6.37E-07 | 9.08E-07 | 5.87E-07 |
| ULO | m2a | 5.15E-04 | 6.05E-04 | 4.99E-04 |
| WD | m3 | 3.82E-05 | 5.54E-05 | 3.49E-05 |

### *6.2.2 Changes in bike weight – specific materials and components*

In this section, we test potential impact variations caused by increases in the three main materials: aluminum, steel and polyethylene. Increments in the use of aluminum causes the

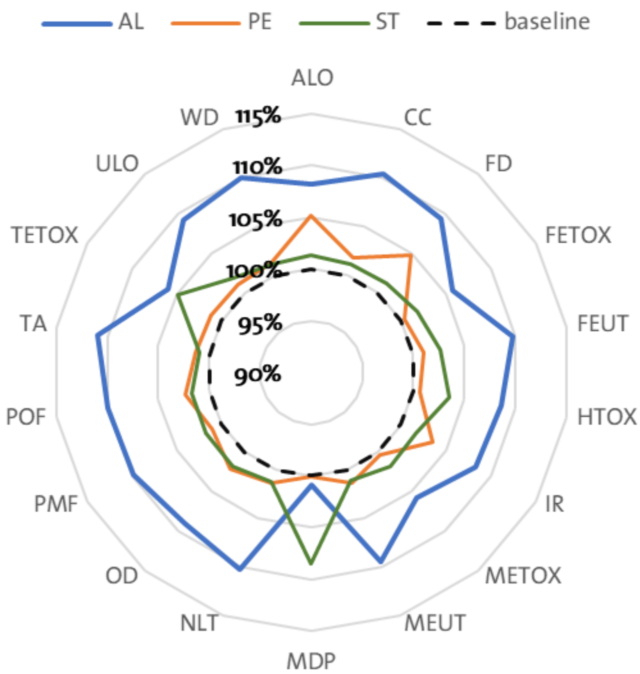


*Figure 8. Figure 8. Baseline case vs alternative weights due to increase in the main materials, i.e., aluminium, steel and polyethylene*

highest increments in all the categories except for the metal depletion (Figure 8): with respect to the impacts caused by the baseline bike production, increments between 0.8% (metal depletion) and 11% (terrestrial acidification) have resulted (i.e., 0.71% and 9.67% on total impacts, respectively). Each kg of steel causes increments between 1% (terrestrial acidification) and 8.5% (metal depletion) (i.e., 0.88% and 7.47% on total impacts, respectively), causing the highest contribution in terms of metal depletion due to the presence of chromium[8]. Finally, each kg of polyethylene causes increases ranging between 0.1% (metal depletion) and 5.1% (agricultural land occupation) (i.e., 0.09% and 3.86% on total impacts, respectively).

Besides testing the influence of generic variations in the amount of materials, we assessed the impact contributions due to the presence of airless or flat-proof tires and of bigger saddles, which are common in bike-sharing bikes (see section 3.3). On the production side, a bigger saddle and the installation of airless tires causes increments in environmental impacts ranging between 0.3% (metal depletion) and 4.9% (water depletion). If we consider the FU of this study, the caused increments range from negligible values (i.e., freshwater and marine ecotoxicity, ionizing radiation, metal depletion and urban land occupation) up to 5% in the

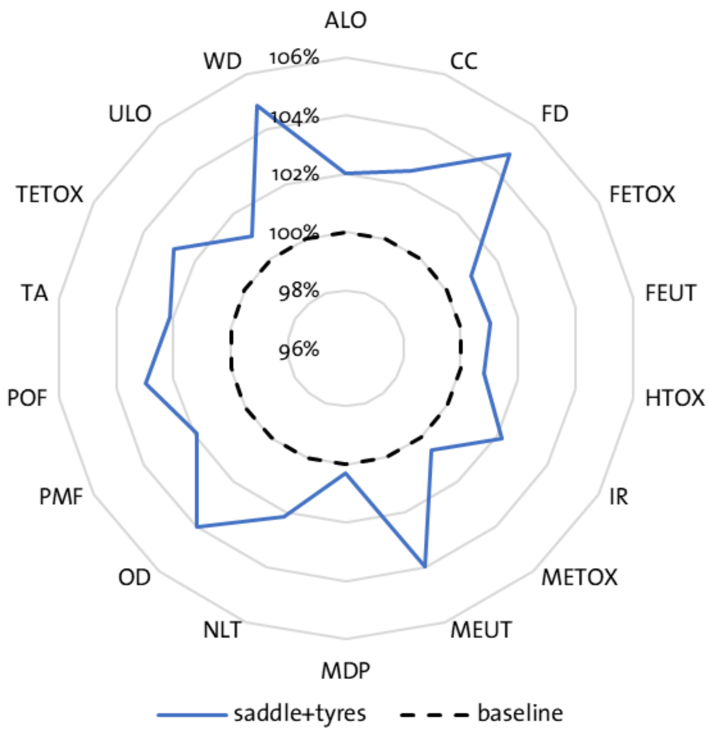


*Figure 9. Baseline case vs alternative weights due to a bigger saddle and installation of flat-proof tires*

case of marine eutrophication (Figure 9).

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[8] Chromium is characterized by a relatively higher characterization factor in this category (kg Fe-eq/kg), for instance, with respect to Aluminum

### *6.2.3 Bike lifespan and substitution of components*

#### *6.2.3.1 Lifespan of the entire bike*

An important assumption behind the model of a bike is the lifespan of the bike. In the baseline case of this study, it is assumed equal to 15,000 km. When testing the sensitivity of environmental impacts to this assumption, we found that the impacts significantly increase while reducing the assumed lifespan according to a (negative) power law (Figure 10, for a focus in Climate Change category): for instance, by reducing the bike life down to 5000 km (1/3 of the baseline assumption), the impacts increases by 1.8 times; and if the life is reduced down to 150 km they will be about 90 times higher.

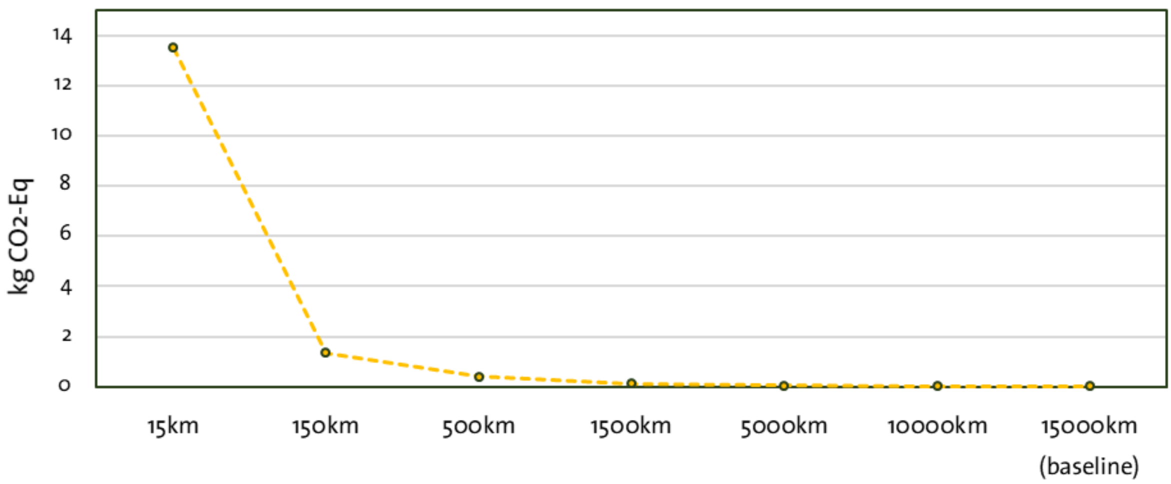


*Figure 10. Bike lifespan influence on the environmental impacts (here we reported only climate change category)*

#### *6.2.3.2 Risk of breakage – different components*

By focusing on the core of the bike sharing service, i.e., the use and maintenance of the bike, we tested how the breakage of bike components and the consequent substitution affects the

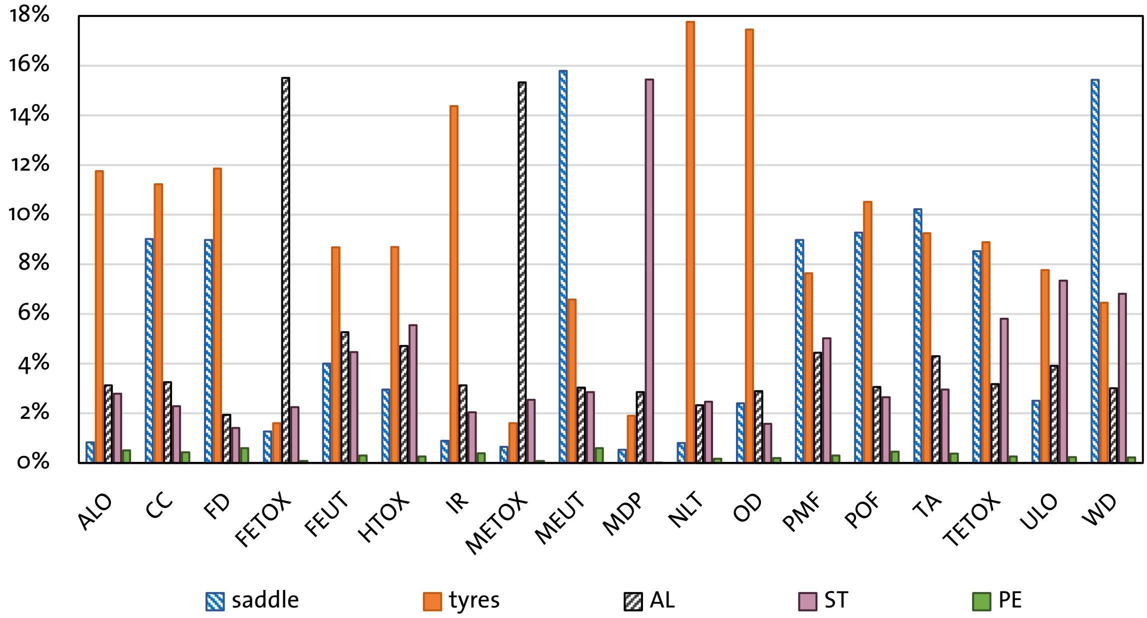


*Figure 11. Bike breakage - increases in the environmental impacts due to the additional material and components substituted with respect to the baseline case (represented by the 0%)*

overall environmental impacts. Figure 11 shows the percentage increments with respect to the only baseline bike maintenance (represented by the 0%). On average, the highest increment is caused by an additional pair of tires (ranging between +1.6% for freshwater ecotoxicity and metal depletion, and +17.8% for natural land transformation), while the substitution of the saddle would cause impact increments ranging from +0.5% (metal depletion) and +15.8% (marine eutrophication). Focusing on the materials, increasing the substitution of the initially assumed amount by 1% causes the highest increments in the case of aluminum (from +1.9% to 15.5%, of fossil depletion and freshwater ecotoxicity, respectively) and lowest increases in the case of polyethylene (from +0.02% to 0.6%, of metal depletion and marine eutrophication, respectively). If we refer those results to the FU of this study, we obtain a maximum increment equal to 3.2% for freshwater ecotoxicity due to additional aluminum, and a minimum increment equal to 0.002% for metal depletion to additional polyethylene. The complete results are reported in section 9.1.2 in the supplementary materials.

### *6.2.4 Bike production site*

The comparison between bike production in China and Europe show that there is not a best option: depending on the impact category, one option can cause the highest or the lowest impacts (Figure 12). For 10 out of 18 impact categories, bike production results worse in the EU case, and mainly because of the average EU electricity production, in particular, waste incineration and nuclear production (especially for ionizing radiation and ozone depletion).

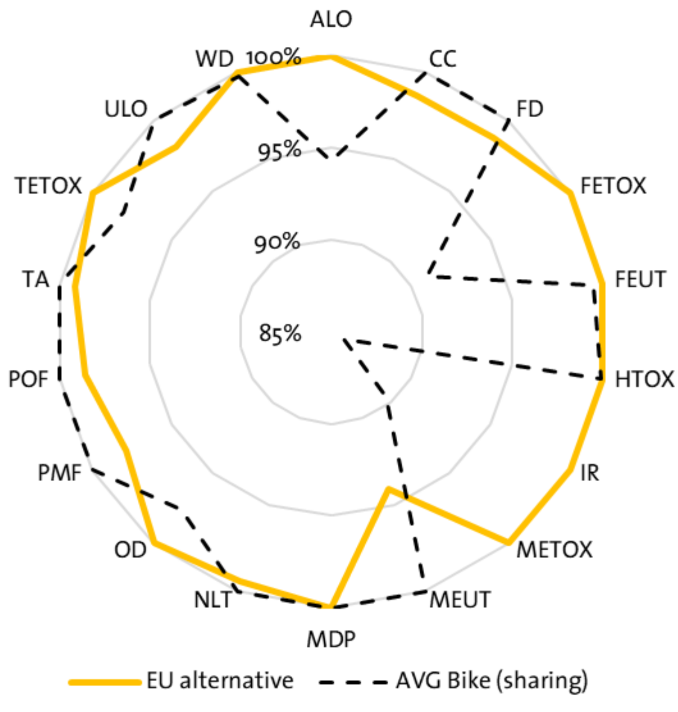


*Figure 12. Bike production: baseline case (Chinese production) vs European production*

## 6.3 Comparison with other transportation means and break-even point determination

By comparing the different urban public or shared transportation means according to the baseline assumptions, the bike-sharing bike results among the best options, only second to the urban train, whose dataset describe the specific case of Switzerland. Given the fact that the lifespan assumed for the bike in the original dataset was define for private bikes, we tested how the comparison changes while changing the lifespan (proportionally to the

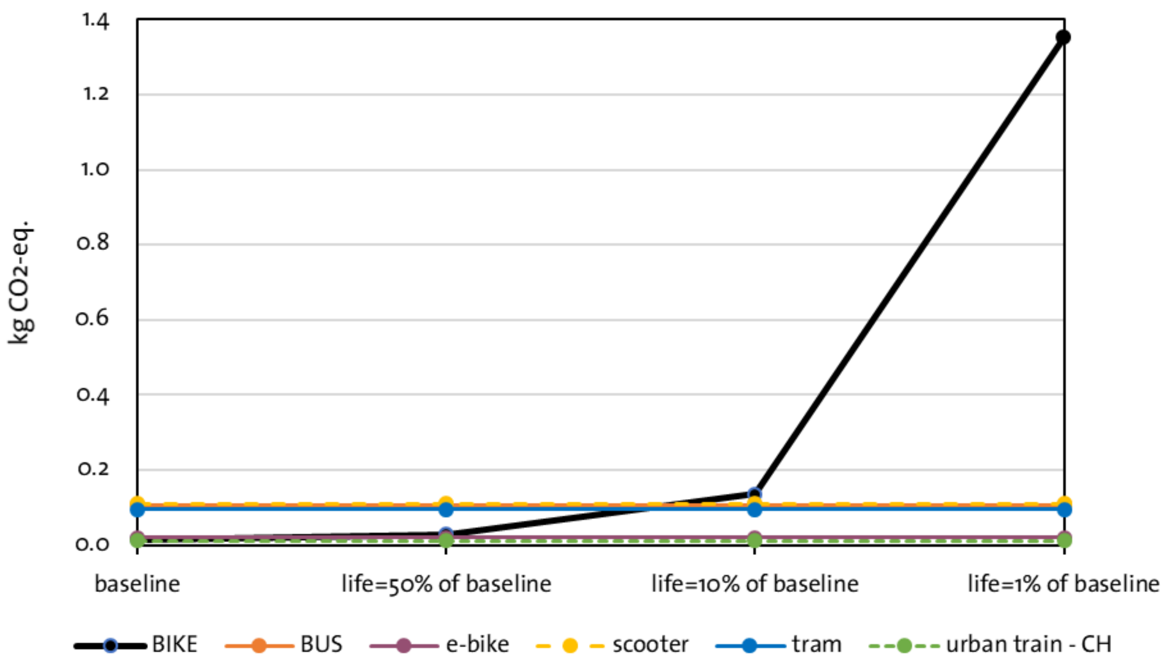


*Figure 13. Urban transportation means comparison - variation in bike lifespan*

baseline value).

Figure 13 shows that with a reduction of 50% in the bike lifespan (i.e., 7,500 km), the baseline e-bike performs better, and with a lifespan equal to 1,500 km (i.e., 10% of the baseline), the bike results the worst with the respect to the baseline scenarios of others transportation means.

In Figure 14, we compare the transportation means assuming the same lifespan reduction for all of them. In this case, besides the urban train, the bike results comparable to the tram when assuming a lifespan equal to 10% of the baseline, and it results worse than tram and bus if the lifespan is assumed equal to 1% of the baseline (i.e., 150 km in the case of bike).

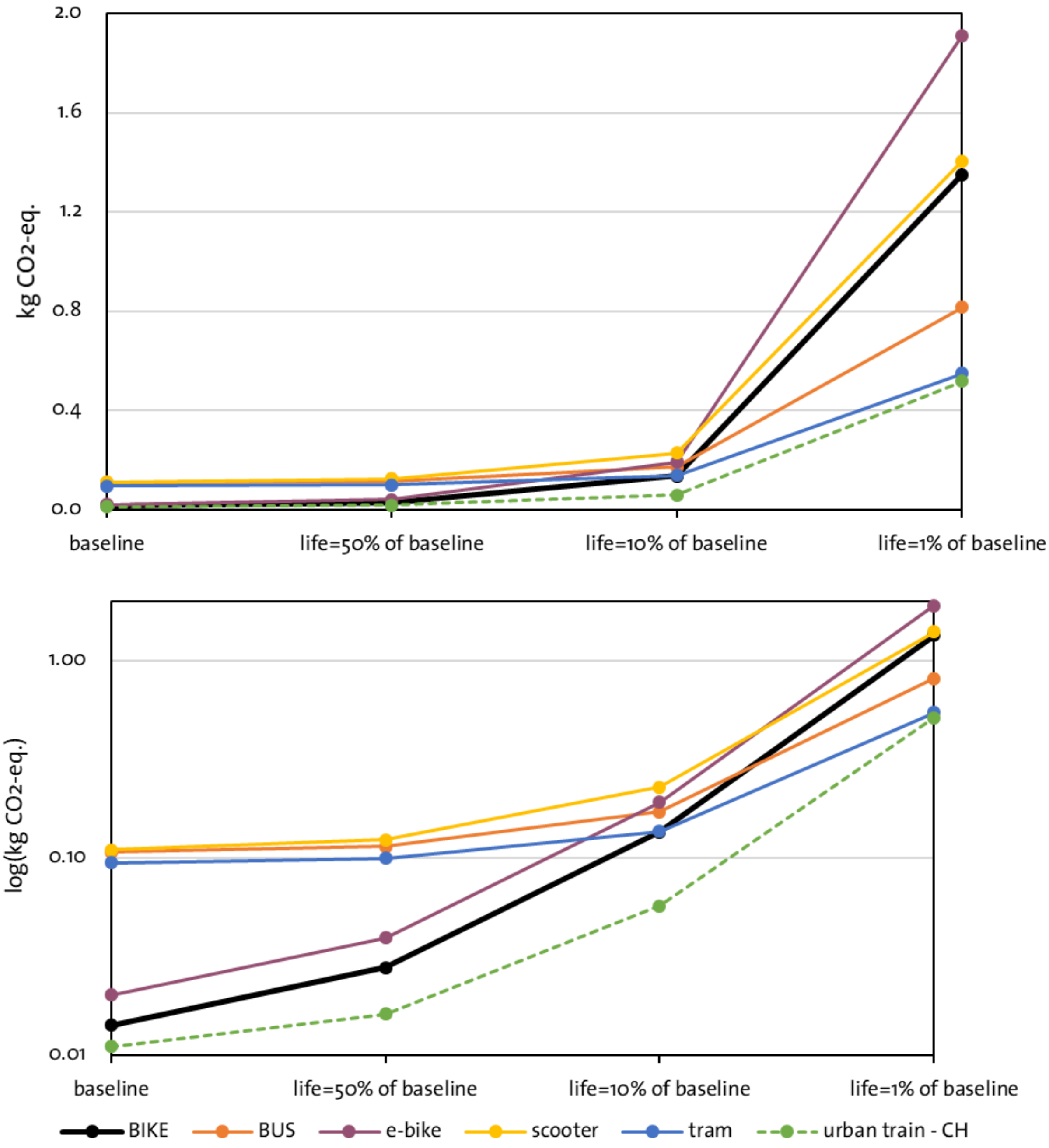


*Figure 14. Comparison between urban public or shared transportation means - influence of the assumption on vehicle lifespan (the lower chart reports a logarithmic scale to improve the readability of the results)*

## 7 Interpretation and discussion

The present study provides an analysis of the environmental dimension of bike-sharing bike under a life cycle perspective. Despite the lack of primary data, the results obtained from the analysis allow to understand the potential environmental impacts caused by bike-sharing bikes, the main causes of these impacts, and how these impacts can vary due to different bike characteristics (e.g., weight and material composition), lifespan and risk of breakage, and how this service performs with respect to other urban public or shared transportation means.

Concerning the life cycle of the bike under the baseline assumptions (i.e., closer to the average condition of a private bike), the bike production resulted the phase with the highest impacts mainly due to the use of metals, in particular, aluminum and steel. When testing the sensitivity of the obtained results to changes in the bike weight and lifespan of bike-sharing bikes, obtained results show a significant influence of these two characteristics (or assumptions) on the environmental impacts: increases of less than 50% in the overall weight of the bikes can cause an increases ranging between 17% (urban land occupation) and 46% (metal depletion); while a potential reduction in weight of future bikes down of about 9% in weight reduces the impacts between -3% (urban land occupation) and -9% (metal depletion). Referring to the single materials and analyzing the three main components in terms of weights, i.e., aluminum, steel and polyethylene, the highest impacts would be caused by increments in aluminum. Concerning the bike lifespan, by reducing the bike life down to 5000 km (i.e., 1/3 of the baseline assumption), the impacts increases by 1.8 times; and if the life is reduced to 150 km, they are about 90 times higher.

During the use phase, the risk or rate of bike breakage can significantly influence the environmental profile of the bike-sharing service. On average, focusing on specific components, the highest increment is caused by additional substitution of tires (ranging between +1.6% for freshwater ecotoxicity and metal depletion, and +17.8% for natural land transformation), while the substitution of the saddle would cause impact increments ranging from +0.5% (metal depletion) and +15.8% (marine eutrophication). Focusing on the materials, the highest increases in environmental impacts would be caused by substitution of aluminum components, while lowest increases in the case of polyethylene (assessing the same amount of material).

Finally, when comparing urban public and shared transportation means the bike-sharing service (assuming the baseline scenario) results among the best available options. But if the lifespan of bike-sharing bikes is reduced due to damages, breakage and vandalism it can results worse than tram and bus. Additionally, potential environmental impacts linked to the use of apps and GSP trackers are excluded from the study and they can increase the environmental impacts of bike-sharing service.

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# 9 Supplementary Materials

### *9.1.1 Inventory – road use*

The calculation steps performed to obtain the *specific road demand per km* for a bike are summarized in Table 12 (complete sources in Leuenberger et al., 2010 [14]).

*Table 12. Calculation steps to obtain the specific road demand per km for a bike*

| ID | Road use and disposal | units | bicycles | Type of data |
|---|---|---|---|---|
| A | length road network | km | 71,600 | External (ecoinvent report No. 14 - Swiss statistics) |
| B | total kilometers by vehicle type | vkm | 1.4E+09 | External (BFS Mikrozensus 2005) |
| C | net-transport performance | pkm | 1.4E+09 | External (BFS Mikrozensus 2005) |
| D | net vehicle weight | t | 1.7E-02 | study |
| E | average load | t | 7.5E-02 | external (average HP) |
| F | average gross vehicle weight | t | 9.2E-02 | F=D*E |
| G | Gross transport performance vehicle | Gtkm | 1.3E+08 | G=F*C |
| H | Gross transport performance total | Gtkm | 1.3E+11 | External (ecoinvent report No. 14 - Swiss statistics) |
| I | Demand of total network | % | 0.094% | I=G/H |
| L | road network used by bikes | m | 67,347 | L=(A*1000) *I |
| M | Specific road demand per km (1 bike) | m*a/p | 4.92E-05 | M=L/C |

### *9.1.2 Impact assessment*

In Table 13, we reported the complete results obtained in the case of weight increases due to installation of bigger saddle and flat-proof tires.

*Table 13. Environmental impacts obtained in the case of installation of bigger saddles and flat-proof tires*

| Name | Unit | Bike production (1 bike) | | Bike life cycle (1 km*person) | |
|---|---|---|---|---|---|
| | | Saddle + tires | Ratio with baseline results | Saddle + tires | Ratio with baseline results |
| agricultural land occupation | m2a | 4.16E+00 | 102.0% | 3.70E-04 | 100% |
| climate change | kg CO2-Eq | 1.90E+02 | 102.5% | 1.45E-02 | 103% |
| fossil depletion | kg oil-Eq | 4.74E+01 | 104.7% | 4.02E-03 | 104% |
| freshwater ecotoxicity | kg 1,4-DCB-Eq | 4.69E+00 | 101.0% | 4.10E-04 | 100% |
| freshwater eutrophication | kg P-Eq | 6.75E-02 | 101.0% | 4.96E-06 | 101% |
| human toxicity | kg 1,4-DCB-Eq | 8.09E+01 | 100.8% | 5.91E-03 | 101% |
| ionizing radiation | kg U235-Eq | 6.43E+00 | 102.2% | 6.00E-04 | 100% |
| marine ecotoxicity | kg 1,4-DCB-Eq | 4.35E+00 | 100.6% | 3.80E-04 | 100% |
| marine eutrophication | kg N-Eq | 1.93E-01 | 104.0% | 1.54E-05 | 105% |
| metal depletion | kg Fe-Eq | 3.10E+01 | 100.3% | 2.35E-03 | 100% |
| natural land transfor- | m2 | 1.94E-02 | 102.2% | 1.87E-06 | 102% |

| | | | | | |
|---|---|---|---|---|---|
| mation | | | | | |
| ozone depletion | kg CFC-11-Eq | 6.53E-06 | 104.0% | 6.90E-10 | 102% |
| particulate matter formation | kg PM10-Eq | 4.77E-01 | 101.9% | 3.71E-05 | 102% |
| photochemical oxidant formation | kg NMVOC | 5.64E-01 | 103.0% | 4.79E-05 | 103% |
| terrestrial acidification | kg SO2-Eq | 9.11E-01 | 102.1% | 6.86E-05 | 102% |
| terrestrial ecotoxicity | kg 1,4-DCB-Eq | 7.96E-03 | 102.8% | 6.49E-07 | 102% |
| urban land occupation | m2a | 1.64E+00 | 101.0% | 5.20E-04 | 100% |
| water depletion | m3 | 5.12E-01 | 104.9% | 3.97E-05 | 104% |

In Table 14 and Table 15, we reported additional results we obtained while testing the increments of rates of breakage (the reported results refer to 1 bike).

*Table 14. Bike breakage risk - complete absolute results*

| Impact cat. ID | baseline | saddle | tires | AL | ST | PE | Unit |
|---|---|---|---|---|---|---|---|
| ALO | 8.0E-01 | 8.1E-01 | 9.0E-01 | 8.3E-01 | 8.2E-01 | 8.1E-01 | m2a |
| CC | 1.8E+01 | 1.9E+01 | 2.0E+01 | 1.8E+01 | 1.8E+01 | 1.8E+01 | kg CO2-Eq |
| FD | 7.2E+00 | 7.9E+00 | 8.1E+00 | 7.4E+00 | 7.3E+00 | 7.3E+00 | kg oil-Eq |
| FETOX | 1.3E+00 | 1.3E+00 | 1.3E+00 | 1.5E+00 | 1.3E+00 | 1.3E+00 | kg 1,4-DCB-Eq |
| FEUT | 4.4E-03 | 4.6E-03 | 4.8E-03 | 4.7E-03 | 4.6E-03 | 4.5E-03 | kg P-Eq |
| HTOX | 5.3E+00 | 5.5E+00 | 5.8E+00 | 5.6E+00 | 5.6E+00 | 5.4E+00 | kg 1,4-DCB-Eq |
| IR | 1.1E+00 | 1.1E+00 | 1.3E+00 | 1.2E+00 | 1.1E+00 | 1.1E+00 | kg U235-Eq |
| METOX | 1.1E+00 | 1.1E+00 | 1.1E+00 | 1.3E+00 | 1.1E+00 | 1.1E+00 | kg 1,4-DCB-Eq |
| MEUT | 1.8E-02 | 2.1E-02 | 1.9E-02 | 1.8E-02 | 1.8E-02 | 1.8E-02 | kg N-Eq |
| MDP | 3.5E+00 | 3.5E+00 | 3.5E+00 | 3.6E+00 | 4.0E+00 | 3.5E+00 | kg Fe-Eq |
| NLT | 2.8E-03 | 2.9E-03 | 3.3E-03 | 2.9E-03 | 2.9E-03 | 2.8E-03 | m2 |
| OD | 1.4E-06 | 1.4E-06 | 1.6E-06 | 1.4E-06 | 1.4E-06 | 1.4E-06 | kg CFC-11-Eq |
| PMF | 3.3E-02 | 3.6E-02 | 3.6E-02 | 3.5E-02 | 3.5E-02 | 3.4E-02 | kg PM10-Eq |
| POF | 5.6E-02 | 6.1E-02 | 6.2E-02 | 5.8E-02 | 5.8E-02 | 5.6E-02 | kg NMVOC |
| TA | 6.2E-02 | 6.9E-02 | 6.8E-02 | 6.5E-02 | 6.4E-02 | 6.2E-02 | kg SO2-Eq |
| TETOX | 8.8E-04 | 9.5E-04 | 9.5E-04 | 9.0E-04 | 9.3E-04 | 8.8E-04 | kg 1,4-DCB-Eq |
| ULO | 1.5E-01 | 1.5E-01 | 1.6E-01 | 1.5E-01 | 1.6E-01 | 1.5E-01 | m2a |
| WD | 6.0E-02 | 6.9E-02 | 6.4E-02 | 6.2E-02 | 6.4E-02 | 6.0E-02 | m3 |

*Table 15. Bike breakage risk - complete relative results (with respect to the baseline case)*

| increments of the total impacts |
|---|

Bike sharing

| Impact cat. ID | saddle | tires | AL | ST | PE |
|---|---|---|---|---|---|
| ALO | 0.1% | 1.7% | 0.5% | 0.4% | 0.07% |
| CC | 0.7% | 0.9% | 0.3% | 0.2% | 0.04% |
| FD | 1.1% | 1.5% | 0.2% | 0.2% | 0.07% |
| FETOX | 0.3% | 0.3% | 3.2% | 0.5% | 0.02% |
| FEUT | 0.2% | 0.5% | 0.3% | 0.3% | 0.02% |
| HTOX | 0.2% | 0.5% | 0.3% | 0.3% | 0.02% |
| IR | 0.1% | 2.0% | 0.4% | 0.3% | 0.05% |
| METOX | 0.1% | 0.3% | 3.0% | 0.5% | 0.02% |
| MEUT | 1.3% | 0.5% | 0.2% | 0.2% | 0.05% |
| MDP | 0.1% | 0.2% | 0.3% | 1.5% | 0.00% |
| NLT | 0.1% | 1.8% | 0.2% | 0.3% | 0.02% |
| OD | 0.3% | 2.4% | 0.4% | 0.2% | 0.03% |
| PMF | 0.6% | 0.5% | 0.3% | 0.3% | 0.02% |
| POF | 0.7% | 0.8% | 0.2% | 0.2% | 0.04% |
| TA | 0.6% | 0.6% | 0.3% | 0.2% | 0.02% |
| TETOX | 0.8% | 0.8% | 0.3% | 0.5% | 0.02% |
| ULO | 0.0% | 0.1% | 0.1% | 0.1% | 0.00% |
| WD | 1.6% | 0.7% | 0.3% | 0.7% | 0.02% |
| max | 1.6% | 2.4% | 3.2% | 1.5% | 0.1% |
| min | 0.0% | 0.1% | 0.1% | 0.1% | 0.002% |
| average | 0.5% | 0.9% | 0.6% | 0.4% | 0.0% |

Bike sharing

## 10 Feedback & Contact

If you have other questions not addressed by this document, or should you need further clarifications on any of the points commented, then please contact us:

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