# biclaR: Estimating the socio-environmental impacts of car substitution by bicycle and public transit using open tools

**Abstract**

A high proportion of car trips can be replaced by a combination of public transit and cycling for the first-and-last mile. This paper estimates the potential for cycling combined with public transit (PT) as a substitute for car trips in the Lisbon metropolitan area and assesses its socio-environmental impacts using open data and open source tools. A decision support tool that facilitates the design and development of a metropolitan cycling network was developed (*biclaR*). The social and environmental impacts were assessed using the *HEAT for Cycling* and the *HEAT as a Service* tools. The impacts of shifting car trips to PT were also estimated and monetized. The results indicate that 10% of trips could be made by bicycle + PT combination. Shifting to cycling for the first-and-last mile stages can reduce annual $CO_2$eq emissions from 6,000 tons/day, with benefits over 10 years of at least €230 million. For the PT leg, the transfer from car avoids of up to 20,500 tons of $CO_2$eq emissions per year. This evidence can support policymakers to prioritize interventions that reduce the reliance on private motor vehicles.

*Keywords:* Active transport, Intermodality, First and last mile, Health economic assessment, Environmental impacts, Open data and methods

## 1. Introduction

Combining public transportation (PT) and cycling for the first and last mile in metropolitan areas can significantly replace private car trips (Martens, 2007; Rietveld, 2000). This approach requires interventions and programs to make bicycling more appealing, and the resulting public investments can have significant social and environmental benefits.

According to the latest mobility survey conducted in 2018 (INE, 2018), the LMA registered a total of 5.3 million daily trips, with only 0.5% by bicycle. Car modal share was 58.4%, while PT accounted for 15.5%. The number of intra-municipal trips — with origin and destination in the same municipality — amounts to 3.5 million trips. This exceeds the number of inter-municipal trips (1.8 million trips), involving travel between different municipalities. Cars and public transport are the most used modes for intercity trips, with cars being the predominant choice for all journeys.

To achieve the cycling targets set by the Portuguese national cycling strategy for 2025 and 2030 (4% and 10%, respectively) (Presidência do Conselho de Ministros, 2019), the Lisbon's Metropolitan Department of

Transport introduced *biclaR*[1], a decision support tool that facilitates the planning, design, and development of a metropolitan cycling network (Félix et al., 2022).

*biclaR* builds on the Propensity to Cycle Tool[2] (PCT), a web application and research project funded by the UK's Department for Transport in 2015 which launched nationally in 2017 as part of the government's Cycling and Walking Investment Strategy. The PCT initially used only origin-destination data for commuting trips as the basis of estimates of cycling potential at zone, route and route network levels (Lovelace et al., 2017). The PCT has been extended to include cycling potential for travel to school in England (Goodman et al., 2019) and other trip types in other countries.[3] However, to the best of our knowledge, this is the first time that the method has been integrated with public transport data using multi-modal routing to estimate the potential and benefits of multi-stage cycling and PT trips.

This paper estimates the potential for combining cycling and PT to substitute car trips in the LMA. After presenting the methods used, it assesses its socio-environmental impacts using open data and open-source tools.

## 2. Methods

### *2.1. Modeling Origin-Destination trips*

The mobility survey data (INE, 2018) is the basis for this project and defines the baseline scenario. Despite being conducted in the pre-pandemic period (2017), this dataset represents the most comprehensive and up-to-date information on urban mobility in Portuguese metropolitan areas (Lisbon and Porto).

We used a method for disaggregating the origins and destinations of trips between the centroids of two districts (same as "parish") to ensure that a district is not solely characterized by a single point of origin and destination for its trips. Aggregating all trips into centroids renders the exercise less realistic, as it excludes a significant portion of short-distance trips, a prevalent characteristic of active mode travel (Lovelace et al., 2022b). The OD Jittering method breaks down a single point (i.e., the centroid of an area) into multiple random points on the existing and neighboring road network, using OpenStreetMap as a reference. This method then distributes the volume of trips within the district among the randomly generated origin-destination pairs.

Using the `odjitter` R package, we employed a maximum disaggregation level of 100 trips per O-D pair for this project. Figure 1 illustrates the contrast between trip representation through the traditional method, which connects a single desire line between each district, and the presentation achieved through the randomization and disaggregation of trips between districts, specifically for the Lisbon metropolitan area.

[1] See biclar.tmlmobilidade.pt.

[2] See pct.bike.

[3] See npt.scot and cruse.bike for examples of the PCT in Scotland and Ireland that include estimates of cycling for other purposes.

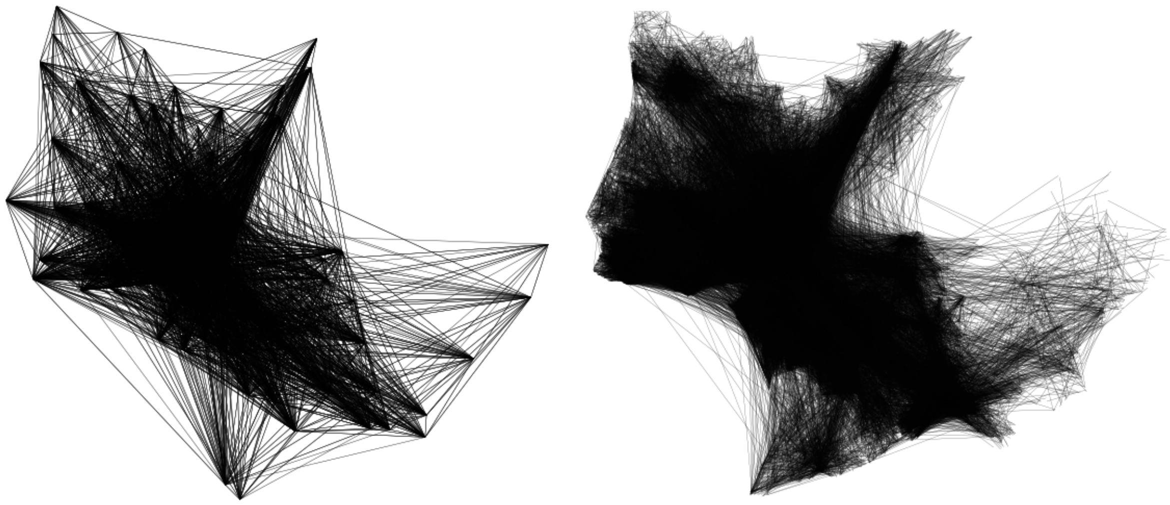

Figure 1: Representation of OD pairs in the Lisbon metropolitan area between districts, without jittering (left) and with jittering (right).

Although this method provides a more realistic representation of the trips undertaken compared to the traditional approach, it does not fully align with the actual O-D pairs of trips, which remain unknown due to data privacy regulations.

### *2.2. Modeling routes*

The mobility survey collects the origin and destination of trips but does not include the respective routes. Modeling the realistic cycling + PT routes between OD pairs depends on assumptions regarding the characteristics of the cycling and road networks and the location of public transport interfaces. Other constraints regarding the behavior of potential cyclists determine the routing results. For example, such restrictions can favor low speed, low traffic streets, more direct routes, and less steep paths, among others, suitable for cycling.

The selected route choice algorithm was the `r5r` R package (Pereira et al., 2021), which allows for great flexibility in configuring estimated route types, and which proven to provide most accurate route networks for the city of Lisbon (Lovelace et al., 2022a). `r5r` can calculate multi-modal routes using PT combined with other modes. It enables the identification of the most direct or safest cycling routes, using the Level of Traffic Stress[4] (LTS) scale, ranging from 1 to 4, where 1 corresponds to the quietest (e.g., off-road cycle paths) and 4 corresponds to the least quiet (e.g., routes shared with motorized traffic). The routes were estimated for the base scenario for both types of networks: *direct* and *safe*, using LTS 4 and LTS 3, respectively. Different routing profiles enable decision-makers to plan for different bicycle user typologies and/or for different city cycling maturity levels (Félix et al., 2017).

[4] see docs.conveyal.com/learn-more/traffic-stress.

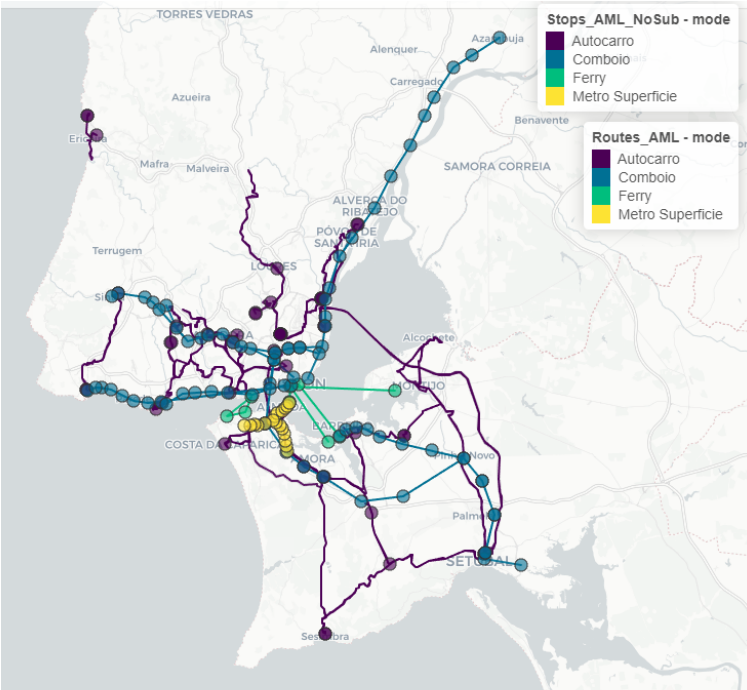


Figure 2: Interfaces and lines considered, by transport mode, in the Lisbon metropolitan area

The `r5r` model used the OpenStreetMap road network and the GTFS metropolitan data aggregated and validated. This information is crucial for an accurate PT trip and route estimation. A digital elevation model, from the European Space Agency's COPERNICUS mission, was used to include street gradient information, as a weight in cycling routing. The cycling potential trips for the two national strategic targets (4% and 10%) were estimated from the 2017 cycling and car trips (both as a driver and as a passenger), the baseline scenario.

The routes were then overlaid and aggregated by segments, using `stplanr overline()` R function.

### *2.3. Modeling intermodality*

The intermodality scenario considers trips combining PT and cycling for the first and last legs. In a conservative approach, we have restricted our analysis to the first and last legs with a combined length of up to 5 km (for instance: 1 km from origin to interface A plus 4 km from interface B to destination) or up to 25 minutes on bike. Furthermore, we have imposed restrictions on PT usage to include only trips with no PT transfers, and up to 2 hours (120 min). Additionally, we have only included PT modes that can easily accommodate bicycles, such as trains, ferries, trams, and inter-municipal bus lines equipped with bike racks (Figure 2).

Figure 3 illustrates the resulting bicycle routes to access the main PT interfaces in the LMA.

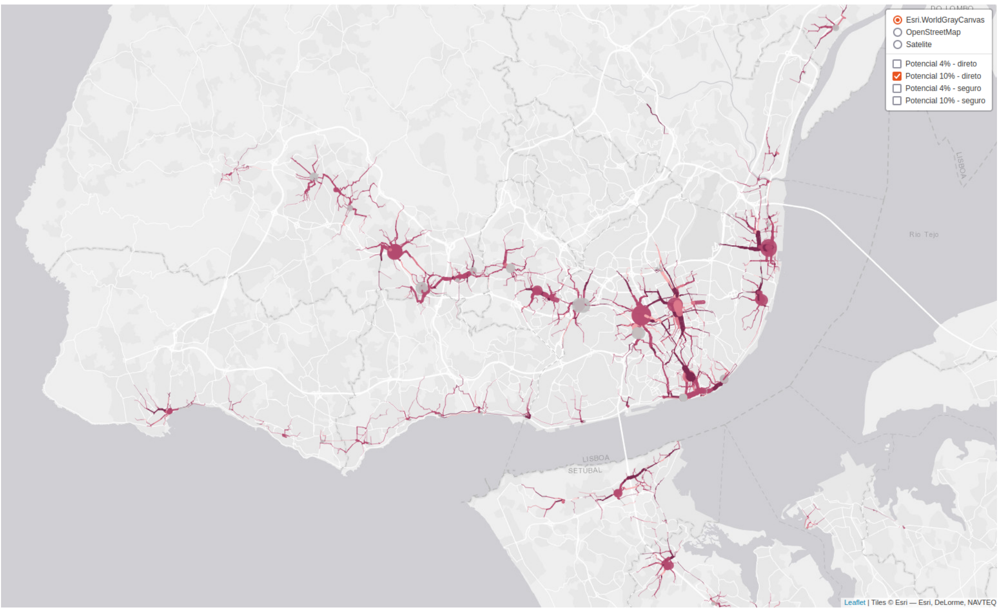


Figure 3: Bike routes with highest potential to serve as first and last leg when replacing cycling and PT from car trips (screenshot of the interactive online tool).

### *2.4. Assessing socio-environmental benefits*

For the cycling legs of the journey (first and last legs), socio-environmental impacts were estimated, using the HEAT for Cycling tool v5.2 (Kahlmeier et al., 2017) from the World Health Organization, and the `HEATaaS` R package[5]. The HEAT tool provided estimates on the shifting from car to cycling for a short term time horizon (i.e., one year) and the long term (i.e., ten years). We considered two dimensions: *social* — including the physical activity of cyclists, air pollution exposure, and road casualties; *environmental* — including $CO_2$eq emissions and other pollutants.

For the second leg of the journey, we estimate the additional environmental impacts of shifting car trips to PT (between the PT interfaces).

To estimate the car emissions, we used the EMEP/EEA's COPERT software v5 methods and reference values (Ntziachristos & Samaras, 2020) for a Tier 3 detail level. We used a family-size vehicle, EURO standard, and gasoline or diesel fuel. All trips were considered to be made under urban conditions and at an average speed of 15 km/h during rush hour periods. Since the average distance traveled per trip influences the overconsumption and emissions from cold-start engine operation, we estimated energy and emission factors for different ranges of trips at 500-meter intervals. In addition, we assumed an occupancy rate of 1.6 passengers *per* car (INE, 2018).

Regarding PT, we considered the emission factor values reported in the environmental and sustainability

[5] `HEATaaS` is under development. For more information contact heatwalkingcycling.org.

Table 1: Summary of the cycling potencial of the intermodality scenario.

| Target | Routing | Total trips | Baseline Cycling + PT | Potencial Cycling + PT |
|---|---|---|---|---|
| 4% | safe | 538 514 | 2 312 | 20 385 |
| 4% | direct | 500 880 | 2 274 | 18 944 |
| 10% | safe | 538 514 | 2 312 | 52 323 |
| 10% | direct | 500 880 | 2 274 | 48 609 |

reports of the PT operators in the LMA (Carris, 2020; CP, 2020; Metropolitano de Lisboa, 2020; Transtejo, 2014).

Emissions were estimated for the following atmospheric pollutants: CO, PM10, NOx, and VOC; and for the main green house gases: $CO_2$, $CH_4$, and $N_2O$, converted in $CO_2$eq. In particular, for the urban train and tram – with 100% electric traction – only $CO_2$eq emissions were considered (resulting from the production of electricity, considering a "well-to-tank" approach), since the other pollutants are not emitted locally.

The conversion of avoided emissions into avoided welfare loss and respective monetary valuation was based on the EU Guide to Cost-benefit Analysis (Sartori et al., 2014) and the best up-to-date reference values for the various gases (Bickel et al., 2006; Nash et al., 2003; Sartori et al., 2014). The social impacts are in avoided premature mortality. This result is finally monetized using the *Statistical Value of Life* for Portugal (Silva et al., 2021). We updated all the monetary reference values of the literature based on the annual inflation rate in Portugal for 2022[6], and our 10-years estimations assumed a discount rate of 5% and inflation of 3%.

## 3. Results and Discussion

Table 1 presents the LMA total daily trips that can be made with cycling + TP combination (with the aforementioned restrictions), the trips in the baseline scenario and corresponding new trips to achieve the national strategy targets (4% and 10%), for different route profiles. For the cycling legs of the journey (first and last legs), the environmental avoided emissions and monetized socio-environment (SE) benefits are presented in 2, resulting from replacing car trips with cycling.

For both *direct* and *safe* route profiles, 10% of the daily trips have the potential to be made by a combination of PT and cycling (up to 5 km on bike). This unveils the potential of cycling as a complementary

[6]See Statistics Portugal tool for inflation rate estimates between years.

Table 2: Summary of the cycling potencial of intermodality scenario and its socio-environmental benefits for the cycling legs.

| Target | Routing | Avoided Mortality (deaths/yr) | Social benefits (k€/yr) | Avoided CO2eq (ton/yr) | Environmental benefits (k€/yr) |
|---|---|---|---|---|---|
| 4% | safe | 4.1 | 12 717 | 2 958 | 238 |
| 4% | direct | 4.0 | 12 441 | 3 004 | 241 |
| 10% | safe | 10.0 | 32 820 | 7 590 | 610 |
| 10% | direct | 10.0 | 31 800 | 7 694 | 618 |

Table 3: Summary of the potential of replacing car trips with cycling in combination with PT, disagregated by PT mode.

| Target | Routing | Potential | Bus | Ferry | Train | Tram |
|---|---|---|---|---|---|---|
| 4% | safe | 20 385 | 573 | 285 | 17 716 | 1 811 |
| 4% | direct | 18 944 | 593 | 313 | 17 093 | 946 |
| 10% | safe | 52 323 | 1 452 | 712 | 45 588 | 4 571 |
| 10% | direct | 48 609 | 1 520 | 781 | 43 932 | 2 375 |

mode of PT, with the potential to uptake the number of PT trips within the LMA area by as much as 6.3% (in addition to the 825 thousand PT trips reported in the mobility survey).

Table 3 shows the potential trips by PT mode to replace the second leg of the journey, in combination with cycling. Train offers the greatest potential for substitution (88%). When comparing the existing PT interfaces (Figure 2) with the bike routes with highest potential to serve as first and last legs (Figure 3) it becomes clear that the Train interfaces are the ones that have the highest potential to attract car-to-PT substituting trips, if their accessibility by bicycle is improved to be safe.

Table 4 presents the results of the avoided emissions and its monetization for the second leg of the journey, by replacing car trips with potential TP trips. Regarding the PT segment, the shift from private car would lead to the mitigation of $CO_2$ equivalent emissions to 8,500 to 20,800 tons annually, valued in €1.4 million to €3.5 million yearly.

The sum of $CO_2$eq avoided emissions from the potential car trips shifted to bike (first-and-last legs) in combination with PT (second leg) in the LMA is presented on Table 5, for both national cycling strategy targets and routing profiles, and the socio-environmental benefits monetized in €, for a 1-year and 10-year time periods.

Shifting from car to cycling + PT can reduce annual $CO_2$eq emissions by 14,000 to 36,000 tons per year. The 10-year socio-environmental benefits account for €235 million to €620 million, depending on the cycling

Table 4: Summary of the avoided emmissions (ton/year) and corresponding monetization (thousand €) by replacing car trips with PT, in the second leg.

| Target | Routing | CO2eq | CO | PM10 | NOx | VOC | Value (k€) |
|---|---|---|---|---|---|---|---|
| 4% | safe | 8 593 | 17 | 1.9 | 27 | 0.8 | 1 425 |
| 4% | direct | 8 702 | 18 | 2.0 | 28 | 0.8 | 1 453 |
| 10% | safe | 20 627 | 42 | 4.6 | 65 | 2.0 | 3 431 |
| 10% | direct | 20 793 | 42 | 4.7 | 66 | 1.9 | 3 487 |

Table 5: Summary of the avoided CO2eq emmissions (ton/year) and the estimated social and environmental benefits (monetized in thousand €) by replacing car trips with cycling in combination with PT.

| Target | Routing | Avoided CO2eq (tons) | SE Benefits 1yr (k€) | SE Benefits 10yrs (k€) |
|---|---|---|---|---|
| 4% | safe | 11 551 | 14 380 | 127 534 |
| 10% | safe | 28 217 | 36 861 | 325 814 |
| 4% | direct | 11 706 | 14 135 | 125 016 |
| 10% | direct | 28 487 | 35 905 | 318 062 |

targets.

The social impacts represent 98% of the socio-environmental benefits (in value) from replacing car trips to bicycle in first-and-last legs. For the PT segment, we did not estimate the social impacts from substituting car trips, although its health benefits would not be as high as shifting to cycling.

The emissions of $CO_2$eq that are avoided during both the initial and final journey segments account for about 75% of the emissions avoided during the PT segment. This finding, while expected – due the zero cycling emissions, should not be overlooked when promoting the PT use. Improving the safe accessibility to PT interfaces to cyclists and providing bicycle-friendly amenities such as parking facilities can potentially lead to a higher reduction in $CO_2$eq emissions, compared to a scenario where individuals shift from car travel to car + PT combination.

Our findings suggest that cycling and PT *in combination* could viably replace 10% of current LMA trips, with an additional 6% of PT journeys prone to further substitution.

There are also social benefits form shifting car trips to PT, nevertheless those were not estimated in this research. One of the main socioenvironmetal benefits, valued after monetization, comes from the increase in physical activity (Félix et al., 2023). The literature shows that the Metabolic Equivalent Tasks (MET) for "riding in a bus or a train" is 1.3 plus the "walking for transportation" is 3.5, while driving a car is 2.5.

see https://golf.procon.org/met-values-for-800-activities/ The difference is not that much between them. Future works should also encompass the estimation of the social impacts for the PT leg of the journey, shifting from car.

## 4. Conclusion

The information on socio-economic benefits can support policy-makers in prioritizing interventions to reduce the reliance on individual motorized transportation, and to better communicate their decisions by providing the expected avoided GHG and air pollutant emissions, and the monetized socio-economic benefits for short and long terms.

The information available at *biclaR* tool – an open access website – can be downloaded and used with any GIS software. This allows practitioners to, for example, gain insights into which potential cycling connections have the highest socio-environmental impacts, quantified in tons of avoided $CO_2$eq emissions, or in long term social benefits.

By making the research process publicly accessible in a code repository, it enables the replication of similar estimates for socio-environmental impacts, resulting from a modal shift from car to bicycle in combination with PT, in other metropolitan areas.

*Acknowledgements.*

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