

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

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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 20% of car trips could switch to the bicycle + PT combination. Shifting to cycling for the first-and-last mile stages can reduce annual CO₂eq emissions from 6,000 tons/day, with benefits over 10 years of €230 million. For the PT leg, the transfer from car avoids of at least 8,500 tons of CO₂eq 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 [1, 2]. 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 [3], 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) [4], the Lisbon’s Metropolitan Department of Transport introduced *biclaR*³, a decision support tool that facilitates the design and development of a metropolitan cycling network [5].

biclaR builds on the Propensity to Cycle Tool⁴ (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 [6]. The PCT has been extended to include cycling potential for travel to school in England [7] and other trip types in other countries.⁵ 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 [3] 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 [8]. 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.

³ See biclar.tmlmobilidade.pt.

⁴ See pct.bike.

⁵ See npt.scot and cruse.bike for examples of the PCT in Scotland and Ireland that include estimates of cycling for other purposes.

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.

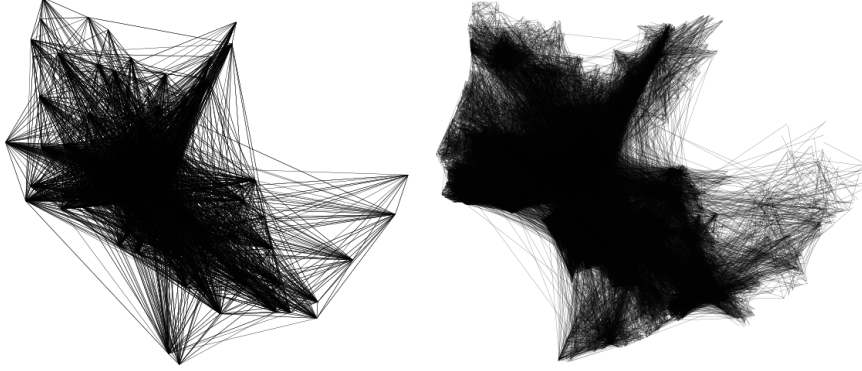


Fig. 1. Representation of OD pairs in the Lisbon metropolitan area between districts, without jittering (left) and with jittering (right).

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](#) [9], which allows for great flexibility in configuring estimated route types, and which proven to provide most accurate route networks for the city of Lisbon [10]. [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 Stress⁶ (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

⁶ see docs.conveyal.com/learn-more/traffic-stress.

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 [11].

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, with a 25m spatial resolution, 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%) was estimated from the values for cycling and car trips (both as a driver and as a passenger) from the 2017 base 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.

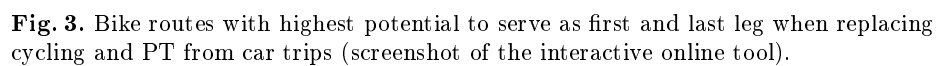
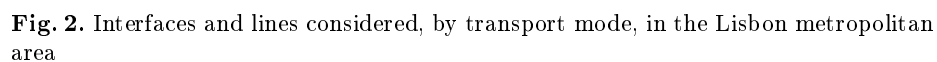
2.4 Assessing socio-environmental benefits

For the cycling legs of the journey (first and last legs), socio-environmental impacts were estimated, using the HEAT for Cycling tool v5.0 [12] and the [HEATaaS R package](#)⁷ from the World Health Organization. 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 CO₂eq 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 [13] 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

⁷ HEATaaS is under development. For more information contact heatwalkingcycling.org.



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 1.61 passengers *per* car [3].

Regarding the PT, we considered the emission factor values reported in the environmental and sustainability reports of the PT operators in the LMA [14–17].

Emissions were estimated for the following atmospheric pollutants: CO₂eq, CO, PM₁₀, NO_x, and VOC. In particular, for the urban train and tram – with 100% electric traction – only CO₂eq 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 [18] and the best up-to-date reference values for the various gases [18–20]. The social impacts are in avoided premature mortality. This result is finally monetized using the *Statistical Value of Life* for Portugal [21]. We updated all the monetary reference values of the literature based on the annual inflation rate in Portugal for 2022⁸, 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, the cycling combined with PT 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 also presented, resulting from replacing car trips with cycling.

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

| Target | Routing | Total trips | Baseline Cycling + PT | Potencial Cycling + PT | Avoided CO ₂ eq (ton/yr) | SE Benefits for 10 years (thousand €) |
|--------|---------|-------------|-----------------------------|------------------------------|---|---|
| 4% | safe | 1 077 028 | 4 624 | 40 770 | 5 920 | 230 270 |
| 4% | direct | 1 001 761 | 4 547 | 37 889 | 6 011 | 223 720 |
| 10% | safe | 1 077 028 | 4 624 | 104 647 | 15 192 | 591 790 |
| 10% | direct | 1 001 761 | 4 547 | 97 218 | 15 414 | 574 200 |

⁸ See [Statistics Portugal tool for inflation rate estimates between years](#).

For both *direct* and *safe* route profiles, 20% of the daily car trips have the potential to be replaced by a combination of PT and cycling (up to 5 km on bike). *Table 2 shows something that doesn't make sense.*

Table 2. Summary of the potential of replacing car trips with cycling in combination with PT, disaggregated by PT mode.

| Target | Routing | Total | Bus | Ferry | Train | Tram |
|--------|---------|---------|-------|-------|---------|--------|
| 4% | safe | 192 214 | 4 163 | 5 167 | 169 984 | 12 900 |
| 4% | direct | 189 846 | 4 879 | 5 795 | 171 534 | 7 639 |
| 10% | safe | 224 152 | 5 042 | 5 594 | 197 857 | 15 659 |
| 10% | direct | 219 511 | 5 806 | 6 263 | 198 373 | 9 069 |

This scenario unveils the potential of cycling as a complementary mode of PT, with the potential to uptake the number of PT trips within the LMA area by as much as 12% (in addition to the 825 thousand PT trips reported in the mobility survey). These findings indicate that transferring car trips to a combination of bicycle and PT could be nearly as substantial, if not equally significant, as the shift towards bicycle-only trips.

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 PT 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 3 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 usage would lead to the mitigation of CO₂ equivalent emissions to 8,500 to 20,800 tons annually, valued in €1.4 million to €3.5 million yearly, with trains offering the greatest potential for substitution (88%).

Table 3. Summary of the avoided emissions (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 |

The sum of CO₂eq 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 4, 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.

Table 4. Summary of the avoided CO₂eq emissions (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 CO ₂ eq (tons) | SE Benefits 1yr (k€) | SE Benefits 10yrs (k€) |
|--------|---------|--------------------------------------|-------------------------|---------------------------|
| 4% | safe | 14 513 | 27 299 | 242 024 |
| 4% | direct | 14 713 | 26 572 | 235 706 |
| 10% | safe | 35 819 | 69 938 | 620 094 |
| 10% | direct | 36 207 | 67 956 | 602 972 |

Shifting from car to cycling + PT can reduce annual CO₂eq emissions by 14,000 to 36,000 tons per year, and the 10-year socio-environmental benefits account for €235 million to €620 million, depending on the cycling targets.

The emissions of CO₂eq 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 CO₂eq emissions, compared to a scenario where individuals shift from car travel to car + PT combination.

The social impacts from replacing car trips to bicycle in first-and-last legs, represent 95% of the total socio-environmental benefits estimated for all journey legs. Our findings suggest that a bicycle and PT combination could viably replace 20% of current LMA trips, with an additional 12% of PT journeys prone to further substitution.

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 to, for instance, understand which

potential cycling connections have the highest socio-environmental impacts, in tons of avoided CO₂eq emissions, or in long term social benefits.

By making the research process publicly accessible in a code repository, this research 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.

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References

1. Martens, K.: Promoting bike-and-ride: The dutch experience. *Transportation Research Part A: Policy and Practice*. 41, 326–338 (2007). <https://doi.org/10.1016/j.tra.2006.09.010>.
2. Rietveld, P.: The accessibility of railway stations: The role of the bicycle in the netherlands. *Transportation Research Part D: Transport and Environment*. 5, 71–75 (2000). [https://doi.org/10.1016/S1361-9209\(99\)00019-X](https://doi.org/10.1016/S1361-9209(99)00019-X).
3. INE: *Mobilidade e funcionalidade do território nas Áreas Metropolitanas do Porto e de Lisboa: 2017*. Instituto Nacional de Estatística, Lisboa (2018).
4. Presidência do Conselho de Ministros: Resolução do conselho de ministros n.º 131/2019, <https://files.dre.pt/1s/2019/08/14700/0004600081.pdf>, (2019).
5. Félix, R., Lovelace, R., Moura, F.: biclaR - Ferramenta de apoio ao planeamento da rede ciclável na área metropolitana de Lisboa, <https://biclar.tmlmobilidade.pt>, (2022).
6. Lovelace, R., Goodman, A., Aldred, R., Berkoff, N., Abbas, A., Woodcock, J.: The Propensity to Cycle Tool: An open source online system for sustainable transport planning. *Journal of Transport and Land Use*. 10, (2017). <https://doi.org/10.5198/jtlu.2016.862>.
7. Goodman, A., Rojas, I.F., Woodcock, J., Aldred, R., Berkoff, N., Morgan, M., Abbas, A., Lovelace, R.: Scenarios of cycling to school in england, and associated health and carbon impacts: Application of the ‘propensity to cycle tool’. *Journal of Transport & Health*. 12, 263–278 (2019). <https://doi.org/10.1016/j.jth.2019.01.008>.

8. Lovelace, R., Félix, R., Carlino, D.: Jittering: A computationally efficient method for generating realistic route networks from origin-destination data. *Findings*. (2022). <https://doi.org/10.32866/001c.33873>.
9. Pereira, R.H.M., Saraiva, M., Herszenhut, D., Braga, C.K.V., Conway, M.W.: r5r: Rapid realistic routing on multimodal transport networks with R5 in r. *Findings*. (2021). <https://doi.org/10.32866/001c.21262>.
10. Lovelace, R., Félix, R., Carlino, D.: Exploring jittering and routing options for converting origin-destination data into route networks: Towards accurate estimates of movement at the street level. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. XLVIII-4/W1-2022, 279–286 (2022). <https://doi.org/10.5194/isprs-archives-XLVIII-4-W1-2022-279-2022>.
11. Félix, R., Moura, F., Clifton, K.J.: Typologies of urban cyclists: Review of market segmentation methods for planning practice. *Transportation Research Record*. 2662, 125–133 (2017). <https://doi.org/10.3141/2662-14>.
12. Kahlmeier, S., Götschi, T., Cavill, N., Castro Fernandez, A., Brand, C., Rojas Rueda, D., Woodcock, J., Kelly, P., Lieb, C., Oja, P., others: [Health economic assessment tool \(HEAT\) for walking and for cycling: Methods and user guide on physical activity, air pollution, injuries and carbon impact assessments](#). (2017).
13. Ntziachristos, L., Samaras, Z.: EMEP/EEA air pollutant emission inventory guidebook 2019, <https://www.emisia.com/utilities/copert/documentation/>, (2020).
14. Carris: [Relatório de sustentabilidade 2019 - demonstração não financeira](#). Carris - Companhia Carris de Ferro de Lisboa, E.M., S.A. (2020).
15. Metropolitano de Lisboa: [Relatório integrado 2019](#). Metropolitano de Lisboa, E.P.E. (2020).
16. CP: [Relatório de sustentabilidade 2019](#). CP - Comboios de Portugal, E.P.E. (2020).
17. Transtejo: [Relatório de sustentabilidade 2014](#). Grupo Transtejo, S.A. (2014).
18. Sartori, D., Catalano, G., Genco, M., Pancotti, C., Sirtori, E., Vignetti, S., Del Bo, C.: [Guide to cost-benefit analysis of investment projects. Economic appraisal tool for cohesion policy 2014-2020](#). European Commission - Directorate General for Regional and Urban Policy (2014).
19. Bickel, P., Friedrich, R., Burgess, A., Fagiani, P., Hunt, A., Jong, G.D., Laird, J.: [HEATCO - Developing Harmonised European Approaches for Transport Costing and Project Assessment. Deliverable 5, Proposal for Harmonised Guidelines](#). (2006).
20. Nash, C., others: [UNification of accounts and marginal costs for transport efficiency: Final report](#). Institute for Transport Studies, University of Leeds (2003).

21. Silva, C., Bravo, J.V., Gonçalves, J.: [Impacto Económico e Social da Sinistralidade Rodoviária em Portugal](#). CEGE - Centro de Estudos de Gestão do ISEG, Autoridade Nacional de Segurança Rodoviária (ANSR) (2021).