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 CO_2eq 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 CO_2eq 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. 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 [1], 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) [2], 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 [3].

biclaR builds on the Propensity to Cycle Tool[4] (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 [4]. The PCT has been extended to include cycling potential for travel to school in England [5] 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 [1] 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 [6]. 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.

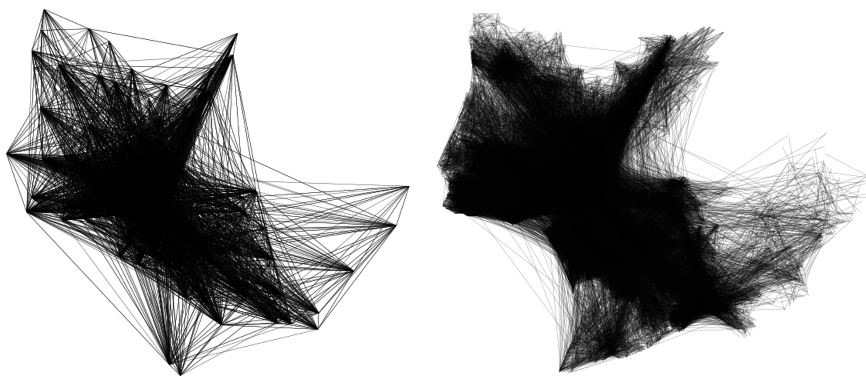

Fig. 1. Representation of OD pairs in the Lisbon metropolitan area between districts, without jittering (left) and with jittering (right).

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 [7], which allows for great flexibility in configuring estimated route types, and which proven to provide most accurate route networks for the city of Lisbon [8]. `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[6] (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.

The `r5r` model used the OpenStreetMap road network and the GTFS metropolitan data agregated 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).

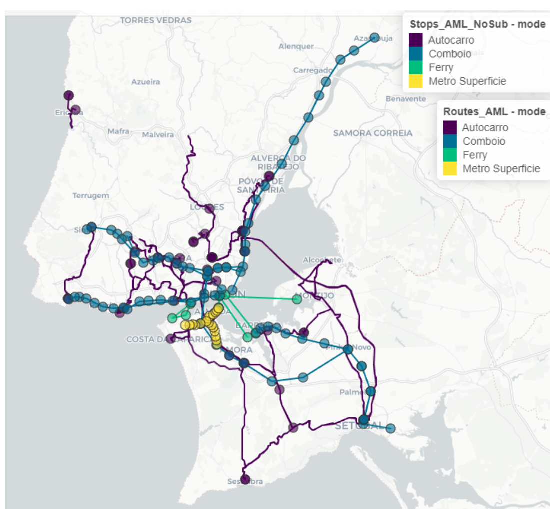

Fig. 2. Interfaces and lines considered, by transport mode, in the Lisbon metropolitan area

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

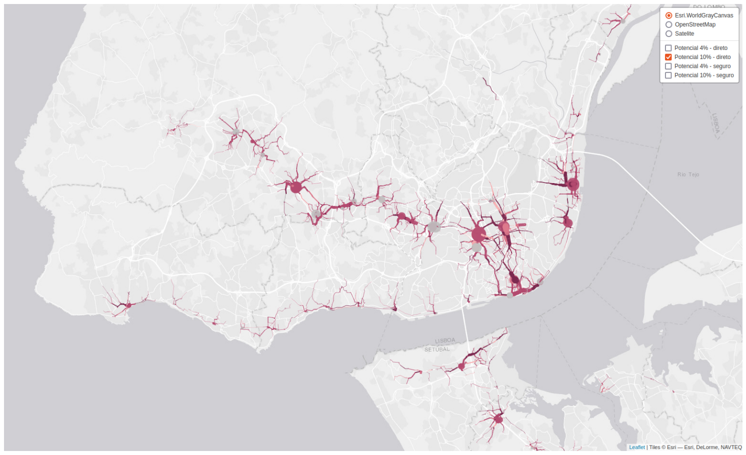

Fig. 3. Bike routes with highest potential to serve as first and last leg when replacing cycling and PT from car trips (screenshot of the interactive online tool).

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 v5.0 [9] 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 CO_2eq 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 [10] 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 1.61 passengers *per* car [1].

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

Regarding the PT, we considered the emission factor values reported in the environmental and sustainability reports of the PT operators in the LMA [11–14].

Emissions were estimated for the following atmospheric pollutants: CO_2eq, CO, PM10, NOx, and VOC. In particular, for the urban train and tram – with 100% electric traction – only CO_2eq 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 [15] and the best up-to-date reference values for the various gases [15–17]. The social impacts are in avoided premature mortality. This result is finally monetized using the *Statistical Value of Life* for Portugal [18]. We updated all the monetary reference values of the literature based on the annual inflation rate in Portugal for 2022[8], 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 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 CO2eq (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

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.

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

Table 2. Summary of the potential of replacing car trips with cycling in combination with PT, disagregated 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 CO_2 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 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

The sum of CO_2eq 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 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	14 513	1 655	244 516
4%	direct	14 713	1 677	238 248
10%	safe	35 819	4 022	626 096
10%	direct	36 207	4 061	609 073

Shifting from car to cycling + PT can reduce annual CO_2eq emissions by 14,000 to 36,000 tons per year, and the 10-year socio-environmental benefits account for €238 to €626 million, depending on the cycling targets.

Say something about the avoided C02eq emissions in the first and last legs (bike) is about 3/4 of the PT leg avoided emissions, which is (expected?) and should not be overlooked when promoting the use of PT. Making the accessibility to PT interfaces more atractive to cycling and providing bicycle-friendly equipments (parking) can reduce more 75% CO2eq emissions than the shifted car to PT trip (FM/RL help)

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 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. Different routing profiles enable decision-makers to plan for different bicycle user typologies and/or for different city cycling maturity levels [19].

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 CO_2eq 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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