CEES 2023 | 2nd International Conference on Construction, Energy, Environment & Sustainability
27-30 June 2023, Funchal - Portugal

THE IMPACT OF CITY FORM AND ACTIVE MODES OF TRANSPORT ON URBAN MOBILITY ENERGY CONSUMPTION

João Coutinho-Rodrigues [1,2]
João Monteiro [3]
Nuno Sousa [1,4]
Eduardo Natividade-Jesus [1,5]

[1] Institute for Systems Engineering and Computers of Coimbra | Portugal
[2] Department of Civil Engineering, University of Coimbra | Portugal
[3] Research Centre for Territory, Transports and Environment (CITTA), Porto | Portugal
[2] Department of Sciences and Technology, Universidade Aberta, Lisbon | Portugal
[2] Department of Civil Engineering, Polytechnic Institute of Coimbra | Portugal
Corresponding author: coutinho@dec.uc.pt

Keywords
City; Transport; Energy; Environment; Sustainability

Abstract
The transport sector is vital in any modern economy, but, during the past century, dependence on vehicles burning petroleum-based fuels has become a defining component of modern societies. Transport share of final global energy consumption is very important - for example, in the EU it accounts for about 32%. On the other hand, sustainable mobility issues, particularly urban mobility, are on the agenda, and it is even predicted that by 2050 there will be no cars running on conventional fuels in cities.
The layout, or form of the city has a decisive impact on energy consumption in urban mobility and the modes of transport used. Active modes of transport, in particular, contribute to reduce transport energy requirements, making it important and timely to consider them in city planning. Estimations using computer models of cities implemented in a GIS environment allow the calculation and comparison of transport energy needs associated with different city forms and allow important conclusions to be drawn about the positive impact of adopting active modes of transport. This research presents test energy calculations carried out both for the current configuration of the city of Coimbra, Portugal, using real georeferenced data of buildings, facilities, jobs, transport infrastructure network, etc., and its redraft as other city forms (e.g., garden city, transit-oriented development city, compact city, 15-minutes city, etc.). Results allow conclusions to be drawn about the associated transport energy needs and modal share, and can provide valuable information to decision makers, infrastructure managers, and planners of more sustainable cities. In practice, the study reveals that in cities with planned urbanism, mobility requires significantly less energy.

1. INTRODUCTION
Cities are the main engines driving our economies, generating over 80% of the world's wealth and consuming between 60-80% of all energy produced on the planet [1]. Urban form is an essential element of urban planning that either can lead towards sustainability or unsustainability [2]. In the past decades, urban transformations due to technological and economic changes have led to urban dispersion [3]. Rapid car-based transport, road investment, and low land values in city suburbs led to the development of urban sprawl, creating a lack of continuity and separating areas of housing, industry and offices, retail, and recreational use [3–5]. Rising concerns over traffic congestion in cities, greenhouse gas emissions (GHG), and transport energy spending has led to a surge of interest in active mobility from academics, practitioners, and policymakers [6–9].
Related to this issue is city form, which influences urban accessibility and mobility, as well as modes of transport and associated energy requirements. In the pursuit of more sustainable cities, active mobility, urban compactification, and densification policies have been widely promoted and adopted [6,8,10,11]. Cycling in particular is a promising mode of transport for urban mobility, ideal for trips up to 5 km [12]. It has low energy intensity and near-zero emissions, and is increasingly recognized as a healthier, cleaner and overall more sustainable mode of transport [13–15]. A good urban design leads directly to better transport planning opportunities [16–18], and urban planning strategies that aim for a higher mix land-use, urban diversification, the development of green spaces, and higher population density have also been suggested as means of planning sustainability [19–21].
The ideal spatial layout of cities has been an active theme of debate for scholars, organizations concerned about the evolution and sustainability of urban areas, and municipal entities aiming to improve the conditions of living of their citizens [22,23]. The past century has been prolific in such debates, with city models being proposed and studied, such as the Garden City, the Radiant City, Transit-Oriented Development, the Transect City, the 15-Minute City or Polycentric Cities [24]. Theoretical debates, however,

lacked adequate quantitative analysis tools that could point out the objective advantages of the different urban design ideas and provide comparisons, either between the models or between those models and real cities. Modern techniques enable us to measure, interpret, and understand the positives and negatives of different city models. The use of geographic information systems (GIS), algorithms, and the powerful tool of datafication allows us to deeply investigate those lacerations of the urban fabric that interrupt the relationship of union between the city space and citizens. The powerful possibilities of simulating the effects and benefits of the redesign of the city, allow us to possess effective tools for economic and political strategies. The governance of future cities will benefit from these surveys and simulations, which are indispensable tools for understanding social dynamics and making the best use of potential energies of creativity, entrepreneurship, and citizen cooperation. Modelling cities to obtain reliable quantitative predictions is a major step in that direction [25,26].

2. METHODOLOGICAL APPROACH

The proposed methodology pivots on a comparative analysis between the city of Coimbra as it is, henceforth designated as "real Coimbra", with its different adaptations to different city model designs. That is to say, the urban layout of real Coimbra is compared to hypothetical, different layouts by geographically redistributing those building blocks so that the city assumes the form dictated by the urban layout(s) one wants to compare with one another. The redistribution should be conducted maintaining the same number of inhabitants and a similar number of urban facilities. The comparison is carried out using three quantitative indicators: accessibility, active transport modal share, transport energy consumption, the latter being related to the two former. For more methodological approach details please see [27–29].

2.1. BENCHMARKING INDICATORS

The three indicators above were selected because of their importance to city planning. A brief motivation for each now follows.

2.1.1. Accessibility

Accessibility is being increasingly incorporated into urban planning guidelines [30,31]. By putting the emphasis on proximity rather than speed, daily living is facilitated without creating a dependency on long distance, fast, and energy-intensive transportation [32,33]. Accessibility is a wide concept that can be interpreted and calculated via different approaches. For this research, it is used the classic definition of accessibility as the ease, or more widely, the cost of reaching destinations. It is given by:

$$A_i = \frac{\sum_{jk} w_j L_{kj} d_{ij}^k}{\sum_j w_j \sum_k L_{kj}}, \quad (1)$$

Where: i: $1, \dots, I$ number of origins; j: $1, \dots, J$ number of facility types; k: $1, \dots, K$ number of closest facilities (when it applies), in this article $K = 3$; A_i: accessibility score of origin i; d_{ij}^k: network distance from origin i to the k-th closest facility of type j (or job zone); w_j: weight of facility type j; L_{kj}: freedom of choice factor for the k-th closest facility of type j; $L_{kj} > L_{k+1,j}$.

2.1.2. Active Modal Share

Active transport, e.g., walking, cycling, is defines transport modes that require human muscular input for locomotion. It is currently one of the main focus of transport planning due to its health benefits, non-polluting, energy efficiency and socioeconomic factors [34–36]. Strategies that encourage the replacement of short-distance car trips by active travel are becoming more popular [37,38]. This research estimates the walk/cycle/car/bus modal split by the methodology of [27,29], which is based on the following ideas:

- The active mode share is estimated from transforming accessibility-related trip distances onto active trip probabilities using log-logistic distributions. Separate walk and walk/cycle probabilities are obtained, the latter by combining walk and cycle probabilities, yielding two types of analysis.
- After discounting the active trip probability, the remaining probability corresponds to motorized trips, which are split onto bus/car trips according to the empirical percentages.

The above analysis is applied to each origin and OD pair. The modal split for origin *i* is then:

$$M_i = \frac{\sum_{jk} w_j L_{kj} p_{Aij}^k}{\sum_j w_j \sum_k L_{kj}}, \quad (2)$$

Where: M_i: active modal share of origin i; $p_{\mathrm{A}ij}^k$: active trip probability from origin i to the k-th closest destination of type j, with $p_{\mathrm{A}ij}^k = \sum_z f_z p_{\mathrm{A}iz}$ for j: jobs ($p_{\mathrm{A}iz}$: active trip probability from i to job centroid z). See [27] for the definition of $p_{\mathrm{A}ij}^k$ and details on $p_{\mathrm{A}iz}$.

The separate scenarios for walk and walk/cycle is justified because many cities do not provide adequate support for the cycling mode (e.g., lack of bikeways and/or lack of mechanical aid devices in hilly cities [39], causing users to steer away from this mode).

2.1.3. Transport Energy Consumption

Measures towards energy conservation and emissions reduction are becoming critical [40], and the urban form and land-use policies are powerful tools to achieve them. Since more compact urban forms are associated with lower consumption and emissions, and fragmentary urban forms (e.g., urban sprawl) are associated with higher consumption and emissions [40–42], it becomes important to have quantitative estimates of energy consumption for those urban layouts. Transport energy consumption is defined as fossil fuel usage on motorized trips (electric vehicles not considered in this study). It is estimated for each origin and OD pair and can be obtained from the motorized modal split using [43]:

$$E_i = \frac{\sum_{jk} w_j L_{kj} \left(1 - p_{Aij}^k\right)\left(f_{car}F_{car} + f_{pub}F_{pub}\right)\left(d_{ijk}^{\rightarrow} + d_{ijk}^{\leftarrow}\right)}{\sum_j w_j \sum_k L_{kj}}, \tag{3}$$

Where: E_i: average fuel consumption of accessibility-related trips originating in i; f_{car}: fraction of motorized trips made using the private car; f_{pub}: fraction of motorized trips made using public transportation; F_{car}: private car average fuel economy (MJ/passenger.km); F_{pub}: public transportation average fuel economy (MJ/passenger.km); $d_{ijk}^{\rightarrow}, d_{ijk}^{\leftarrow}$: one-way distances from origin i respectively towards/away the k-th closest destination of type j.
The E_i is measured in MJ/passenger-trip (at the tank). Note that in eq. (4) trips are always considered two-way, regardless of facility type.

2.2. GIS IMPLEMENTATION

The bulky quantitative analyses required to calculate indicator values are carried out in a GIS environment using solely the geographic characteristics of the spatial layout of the urban areas. The GIS component of the methodology can be summarised as follows:

1. Coimbra urban area was selected for study. Three datasets are collected and curated into a GIS environment: origins (O), destinations (D), and road network. Origins represent demand (for trips) and are the centroids of buildings (endowed with inhabitant number information). Destinations represent supply and are urban facilities and centroids of job zones. The road network connects origins to destinations. Origins and destinations are point feature classes, and the road network is a polyline feature class.
2. In a copy of the datasets, new buildings and facilities are positioned in vacant urban spaces, job zones are remade, and connecting roads are drawn. The buildings house population from the outskirts and are endowed with inhabitant information.
3. For every origin of each layout, network distances are evaluated in GIS to (a) the nearest urban facilities of each type and (b) the centroid of each job zone.
4. Four transport modes are considered: walking, cycling, private motorised transportation, and public transport. For each OD pair, trip probabilities for all those modes are obtained; Indicator values for each origin are then calculated for both the real and the compact layouts based on OD distances and trip probabilities.
5. From the indicator values, statistical measures and maps are derived for the two layouts.

Urban facility types and respective destination attractiveness are here represented by weights as given in Table 1 below. An empirical 1–2–3 Likert scale for weights was used in the research, based on trip frequency, with three the most frequent. Higher weights mean trips to the corresponding destinations are likely to be more frequent. For some facility types, only the closest facility is relevant (e.g., primary healthcare, parks), whereas for others (e.g., restaurants), inhabitants usually want to choose between multiple facilities. The closest-only facilities are marked with an asterisk in Table 1. One- and two-way facilities are indicated in Table 1 by the I or II.
Destinations of the job type require a different approach; as a person usually has only one job, the concept of "nearest job" does not apply. In addition, precise job destination figures require knowing where the people from each origin work, which, in turn, requires large scale surveys, which are, in general, unavailable. Thus, this research uses traffic zone analysis to approach job accessibility. This is implemented as follows: identify job locations and employee count; assign these to a 'jobs' point feature class; divide the city into zones and create a 'job zones' polygon feature class; count jobs in each zone (intersect 'jobs' and 'job zones'); and find the geometric average job location of each zone (GIS *Mean Center* spatial statistics tool). Finally, for each origin, calculate the distance to each job zone geometric average. Jobs are considered one-way facilities and their weight is proportional to the percentage of commuting trips within the study area. All job zones centroids are considered as destinations, and a ponderation by the fraction of jobs in each zone is later applied.

Table 1. Facility types and jobs weights.

Weight 1 facilities	Weight 2 facilities	Weight 3 facilities	Weight 22 facilities
Post offices *II	High Schools I	Kindergartens *II	Jobs I
Sports facilities I	Shopping centres II	Primary schools *II	
Cultural organizations I	Entertainment sites I	Middle Schools *I	
Universities and institutes I	Primary healthcare services *I	Grocery stores II	
Elderly care centres I	Pharmacies *II	Supermarkets II	
Churches I	Restaurants I	Bakeries and pastries II	
	Parks and green areas *I		

(*) Closest only, (I) One-way facility, (II) Two-way facility.

2.3. STUDY CASE

The methodology was applied to the city of Coimbra, Portugal, a mid-size city with approximately 104,000 inhabitants [44]. Coimbra had a compact layout during its origin and medieval times and up to the twentieth century, having then developed onto a sprawled, low-density, and low-mix pattern of land use, with long and wide streets to accommodate the motorised traffic that came in the wake of the cheap fuel boom of the second half of the twentieth century.

Data from Metro Mondego [45] disclose that the active modal share is approximately 22%, of which an abysmal 0.2% is cycling. The empirical motorized share splits as $f_{\text{car}} = 0.7$ and $f_{\text{pub}} = 0.3$, and the share of commuting trips is 37% (survey data), leading to w = 22, j: jobs. Concerning fuel economy, IEA [46] averages were used, namely 1.8 MJ/passenger.km for private cars and 0.7 MJ/passenger.km for public transport.

To redraft Coimbra as the different models, the descriptions and blueprints of each model were followed, with adaptations stemming from Coimbra being a city of services, with healthcare and higher education as main activities. The city of Coimbra was redrafted as:

- The Garden City model by Ebenezer Howard (1898): A city of parks, with large and central green public areas, divided into almost self-sustain wards. Wide avenues with almost every urban facility in the proximity [47].
- Projet de Ville Radieuse by Le Corbusier (1920): From the creator of La Unité D'habitation, large buildings with vertical mix land-use, self-sustainable. Public green landscape, with a clear road hierarchy [48].
- Transit Oriented Development – TOD (1980/90s): Mobility based on public transport defines the urban planning, with distances below 600m to a public transport station, comfortable for almost everyone to walk or cycle. Prioritize mix land-use [49].
- Compact City Theory (1990s). Compacting cities to the extreme: high densification, mix land-use and vertical development into skyrises [50].
- Transect Planning (2000s). A rural-to-urban transect with increasing degree of compactification and densification towards the centre. Zoning system with walkable streets, mixed land use and high transport accessibility, replacing conventional single use zoning systems with six different zones ranging from rural, sub-urban to urban [51,52].
- Infill Coimbra: Minimizing urban sprawl while obeying to the master plan of the city, following the methodology of [29], by moving sprawled urban areas onto more central areas that exist but are not being used currently.

3. RESULTS

The benchmarking indicators results for each model is presented on Table 2. Results show that every model concept can improve on all benchmarking indicators in comparison to the real city of Coimbra (already considering the full cycling potential). The Compact City Concept has the best results for the three indicators. The more compact the city is, the better it scores in the benchmarking indicators. Interestingly, three groups of city model can arguably be defined from similarity of indicator values: the ultra-compact group (Compact City, TOD, Transect), which goes all-in in compactification; and the pleasantness-oriented group (Ville Radieuse, Garden City), which tries to combine efficiency with a greener and more pleasant and vibrant urban environment; Infill Coimbra, whose sprawl is minimized [29], also has scores similar to the pleasantness-oriented group; and the real city (Coimbra), whose sprawl compromises indicator results.

Table 2. Benchmarking indicators results for the different models.

Benchmarking indicators		Compact City Theory	TOD	Transect Planning	Ville Radieuse	Garden City	Infill Coimbra	Coimbra
Accessibility (m)	Min	459	480	448	1010	1194	948	1063
	Average	573	626	647	1234	1487	1570	2533
	Max	745	1008	1484	1818	1914	3092	9329
Active modal share (%)	Min	82.1	70.2	56.5	44.0	53.3	29.0	3.5
	Average	88.0	86.3	85.1	66.9	62.3	58.0	42.5
	Max	92.0	91.0	91.8	73.0	68.3	76.3	74.0
Transport energy consumption (MJ/p.t.)	Min	0.2	0.2	0.2	1.3	1.8	1.3	1.7
	Average	0.4	0.4	0.5	1.9	2.7	2.9	5.8
	Max	0.7	1.4	2.5	3.4	4.0	7.3	26.4

A detailed comparison between the real Coimbra, a Coimbra with full cycling potential and a Infill Coimbra is presented in Table 3. Real Coimbra is represented by the scenario where cycling is not available. Previous work has proven that Coimbra does not have the necessary infrastructure to use bicycles in a safe and comfort manner [27,53]. To the lack of infrastructure, it is also required support infrastructure and a cycling culture that is still being slowly built in Portugal, as for now, someone who rides a bicycle daily is still seen as someone with low income, students that don't have a driving license or cycling fanatic; fortunately, this mentality is slowly changing, and cities need to react. Coimbra will full cycling mode (walking + cycling scenario) measures that potential: a city that is fully capable of harvest all its cycling potential. These two scenarios are compared with the Infill Coimbra, a model that was created from the original city buy compactifying it, i.e., filling in the spaces available in the city. This

compactification did not incur on densification, but rather it complied with the current municipal plans (PDM). It follows mix land-use policies, protected areas, building standards and new residential buildings according to the current regulations.
Figures 1, 2 and 3 give map representations of Table 3 results, in which the effects of compactification on active mobility and transport energy can be visually seen.

Table 3. Effects of compactification on active mobility and active mobility in Coimbra: indicator improvements.

Indicator	Statistics							
	Facilities				Facilities + jobs			
Accessibility (m)	Coimbra	Infill Coimbra	Reduction (m)	Reduction (%)	Coimbra	Infill Coimbra	Reduction (m)	Reduction (%)
Avg.	1936	594	1342	69%	3088	1491	1597	52%
Avg. per inhab.	1440	638	802	56%	2533	1570	963	38%
	Walking				Walking + Cycling			
Active modal share (%) (Fac. + jobs)	Coimbra	Infill Coimbra	Increase	Increase (%)	Coimbra	Infill Coimbra	Increase	Increase (%)
Avg.	12.7	28.1	15.4	121%	35.6	61.6	26.0	73%
Avg. per inhab.	16.8	25.6	8.8	52%	42.6	58.9	15.4	36%
	Walking				Walking + Cycling			
Transport energy (MJ/p.t.) (Fac. + jobs)	Coimbra	Infill Coimbra	Reduction (MJ/p.t.)	Reduction (%)	Coimbra	Infill Coimbra	Reduction (MJ/p.t.)	Reduction (%)
Avg.	8.180	2.056	6.124	75%	6.700	0.954	5.746	86%
Avg. per inhab.	5.901	2.254	3.647	62%	4.533	1.103	3.430	76%

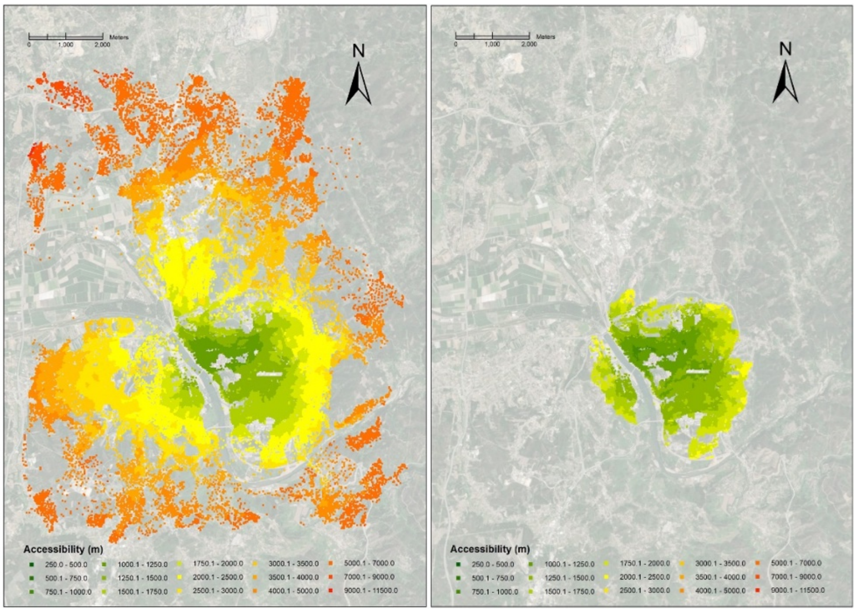

Figure 1. Accessibility to urban facilities plus jobs (m): Coimbra and Infill Coimbra

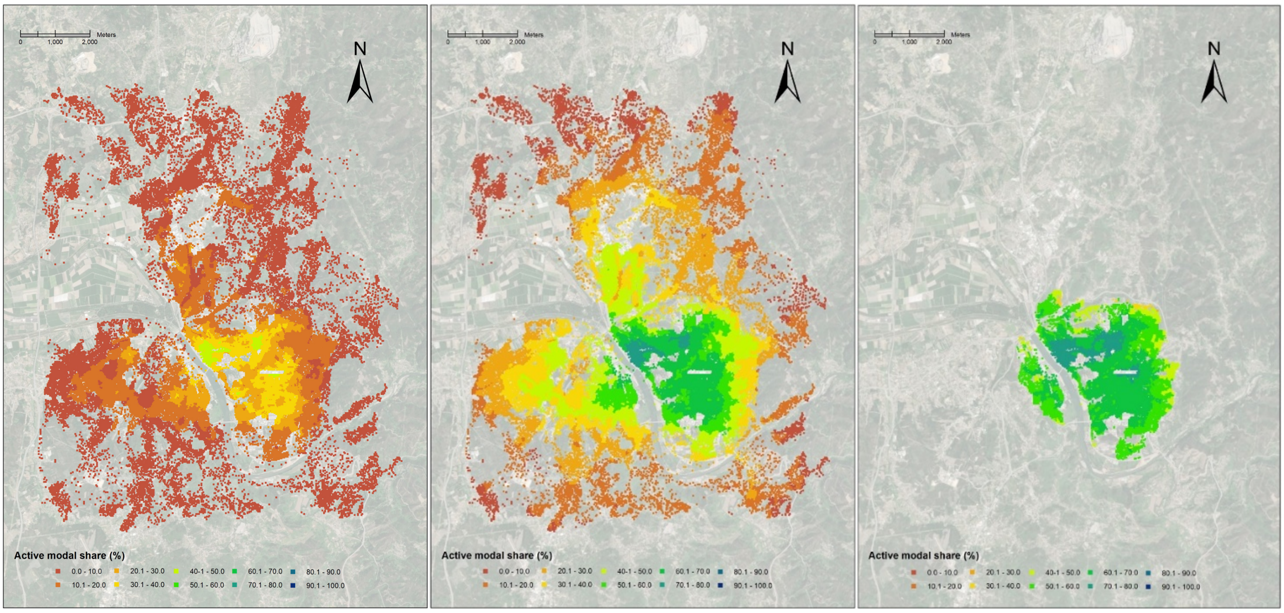

Figure 2. Active modal share to urban facilities plus jobs (%): Coimbra (walk [left], walk+cycle [middle]) and Infill Coimbra (walk+cycle [right])

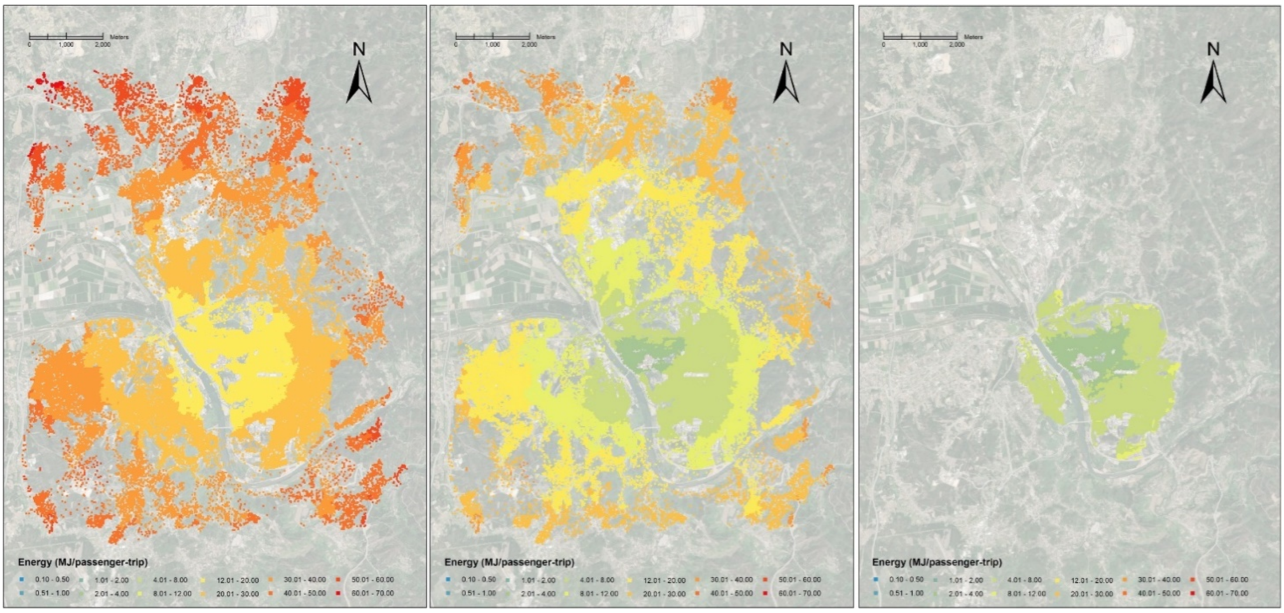

Figure 3. Energy transport consumption to urban facilities plus jobs (MJ/pass.-trip): Coimbra (walk [left], walk+cycle [middle]) and Infill Coimbra (walk+cycle [right])

4. CONCLUSION

The past few decades brought forth new perspectives on sustainability, and urban areas should be prepared for the future. Such paradigms include better accessibility and overall proximity, compacting cities and fighting back urban sprawl, citizen equity, and a rising importance of public green spaces and recreational areas; the latter having an impact on quality of life, city pleasantness, and the environment. A good urban design also leads directly to better transport planning opportunities and, currently, one of the main focuses of transport planning is the active modes, its health benefits, and potential for lower energy consumption.

Comparing the more compact city models with real Coimbra shows that urban sprawl posed a toll on all measures. The higher accessibility of the theoretical constructs is due to shorter OD distances and has an objectively positive effect at various levels. Less energy spent on travel results in lower greenhouse gas emissions (GHG). These concepts also have non-tangible effects on public transport network and ridership, as they lead to more users within reasonable catchment areas of public transport. Regardless of the social levers that led to inequity in the current city, these concepts present themselves as a possible instrument to fight this status-quo and ensure a more equitable and fair development. With the right set of urban policies and adequate promotion, new construction undertakings can improve cities and urban areas. It is not about completely rebuilding a city area or destroying what is already there to build something completely different. It is about efficiently using urban areas that for different reasons are yet undeveloped (e.g., city expansions), have been forgotten, or need to be redeveloped. This study shows that benchmarking real cities versus classic and contemporary city models is possible with the proposed methodology, which can (and should) be extended to other benchmarking indicators and city layouts. This would open new windows of research on the debate on the ideal form of cities, as well as allowing for a better understanding of how to plan upcoming city expansions.

Acknowledgements

This research was partially funded by the Portuguese Foundation for Science and Technology (FCT), grant numbers UIDB/00308/2020 and PD/BD/150589/2020.

References

1. UN Habitat *The Strategic Plan for 2020-23*; 2020;
2. Kakar, K.A.; Prasad, C.S.R.K. Impact of Urban Sprawl on Travel Demand for Public Transport, Private Transport and Walking. *Transportation Research Procedia* **2020**, *48*, 1881–1892, doi:10.1016/j.trpro.2020.08.221.
3. Alonso, A.; Monzón, A.; Cascajo, R. Measuring Negative Synergies of Urban Sprawl and Economic Crisis over Public Transport Efficiency: The Case of Spain. *International Regional Science Review* **2018**, *41*, 540–576, doi:10.1177/0160017616687361.
4. Nechyba, T.J.; Walsh, R.P. Urban Sprawl. *Journal of Economic Perspectives* **2004**, *18*, 177–200, doi:10.1257/0895330042632681.
5. Frumkin, H. Urban Sprawl and Public Health. *Public Health Rep* **2002**, *117*, 201–217.
6. Li, Y. Towards Concentration and Decentralization: The Evolution of Urban Spatial Structure of Chinese Cities, 2001–2016. *Computers, Environment and Urban Systems* **2020**, *80*, 101425, doi:10.1016/j.compenvurbsys.2019.101425.
7. Holienčinová, M.; Kádeková, Z.; Holota, T.; Nagyová, Ľ. Smart Solution of Traffic Congestion through Bike Sharing System in a Small City. *Mobile Netw Appl* **2020**, *25*, 868–875, doi:10.1007/s11036-020-01516-4.
8. Bucher, D.; Buffat, R.; Froemelt, A.; Raubal, M. Energy and Greenhouse Gas Emission Reduction Potentials Resulting from Different Commuter Electric Bicycle Adoption Scenarios in Switzerland. *Renewable and Sustainable Energy Reviews* **2019**, *114*, 109298, doi:10.1016/j.rser.2019.109298.
9. de Nazelle, A.; Nieuwenhuijsen, M.J.; Antó, J.M.; Brauer, M.; Briggs, D.; Braun-Fahrlander, C.; Cavill, N.; Cooper, A.R.; Desqueyroux, H.; Fruin, S.; et al. Improving Health through Policies That Promote Active Travel: A Review of Evidence to Support Integrated Health Impact Assessment. *Environment International* **2011**, *37*, 766–777, doi:10.1016/j.envint.2011.02.003.
10. Artmann, M.; Inostroza, L.; Fan, P. Urban Sprawl, Compact Urban Development and Green Cities. How Much Do We Know, How Much Do We Agree? *Ecological Indicators* **2019**, *96*, 3–9, doi:10.1016/j.ecolind.2018.10.059.
11. Bibri, S.E. Compact Urbanism and the Synergic Potential of Its Integration with Data-Driven Smart Urbanism : An Extensive Interdisciplinary Literature Review. *Land Use Policy* **2020**, *97*, 104703, doi:10.1016/j.landusepol.2020.104703.
12. Dekoster, J.; Schollaert, U. *Cycling: The Way Ahead for Towns and Cities*; Office for Official Publications of the European Commission: Luxembourg, 1999; ISBN 978-92-828-5724-3.
13. Banerjee, A.; Łukawska, M.; Jensen, A.F.; Haustein, S. Facilitating Bicycle Commuting beyond Short Distances: Insights from Existing Literature. *Transport Reviews* **2022**, *42*, 526–550, doi:10.1080/01441647.2021.2004261.
14. Rosas-Satizábal, D.; Guzman, L.A.; Oviedo, D. Cycling Diversity, Accessibility, and Equality: An Analysis of Cycling Commuting in Bogotá. *Transportation Research Part D: Transport and Environment* **2020**, *88*, 102562, doi:10.1016/j.trd.2020.102562.
15. Handy, S.; van Wee, B.; Kroesen, M. Promoting Cycling for Transport: Research Needs and Challenges. *Transport Reviews* **2014**, *34*, 4–24, doi:10.1080/01441647.2013.860204.
16. Rode, P. Urban Planning and Transport Policy Integration: The Role of Governance Hierarchies and Networks in London and Berlin. *Journal of Urban Affairs* **2019**, *41*, 39–63, doi:10.1080/07352166.2016.1271663.
17. Hu, N.; Legara, E.F.; Lee, K.K.; Hung, G.G.; Monterola, C. Impacts of Land Use and Amenities on Public Transport Use, Urban Planning and Design. *Land Use Policy* **2016**, *57*, 356–367, doi:10.1016/j.landusepol.2016.06.004.
18. Giles-Corti, B.; Vernez-Moudon, A.; Reis, R.; Turrell, G.; Dannenberg, A.L.; Badland, H.; Foster, S.; Lowe, M.; Sallis, J.F.; Stevenson, M.; et al. City Planning and Population Health: A Global Challenge. *The Lancet* **2016**, *388*, 2912–2924, doi:10.1016/S0140-6736(16)30066-6.
19. Abdullahi, S.; Pradhan, B. Land Use Change Modeling and the Effect of Compact City Paradigms: Integration of GIS-Based Cellular Automata and Weights-of-Evidence Techniques. *Environ Earth Sci* **2018**, *77*, 251, doi:10.1007/s12665-018-7429-z.
20. Cheng, Y.-H.; Chang, Y.-H.; Lu, I.J. Urban Transportation Energy and Carbon Dioxide Emission Reduction Strategies. *Applied Energy* **2015**, *157*, 953–973, doi:10.1016/j.apenergy.2015.01.126.
21. Stevenson, M.; Thompson, J.; de Sá, T.H.; Ewing, R.; Mohan, D.; McClure, R.; Roberts, I.; Tiwari, G.; Giles-Corti, B.; Sun, X.; et al. Land Use, Transport, and Population Health: Estimating the Health Benefits of Compact Cities. *The Lancet* **2016**, *388*, 2925–2935, doi:10.1016/S0140-6736(16)30067-8.
22. Kristjánsdóttir, S. Roots of Urban Morphology. *ICONARP International Journal of Architecture and Planning* **2019**, *7*, 15–36, doi:10.15320/ICONARP.2019.79.
23. Tellier, L.-N. *Urban World History: An Economic and Geographical Perspective*; Springer International Publishing: Cham, 2019; ISBN 978-3-030-24841-3.
24. Sharifi, A. From Garden City to Eco-Urbanism: The Quest for Sustainable Neighborhood Development. *Sustainable Cities and Society* **2016**, *20*, 1–16, doi:10.1016/j.scs.2015.09.002.

25. Barthelemy, M. Modeling Cities. *Comptes Rendus Physique* **2019**, *20*, 293–307, doi:10.1016/j.crhy.2019.05.005.
26. Phillis, Y.A.; Kouikoglou, V.S.; Verdugo, C. Urban Sustainability Assessment and Ranking of Cities. *Computers, Environment and Urban Systems* **2017**, *64*, 254–265, doi:10.1016/j.compenvurbsys.2017.03.002.
27. Monteiro, J.; Sousa, N.; Natividade-Jesus, E.; Coutinho-Rodrigues, J. The Potential Impact of Cycling on Urban Transport Energy and Modal Share: A GIS-Based Methodology. *ISPRS International Journal of Geo-Information* **2023**, *12*, 48, doi:10.3390/ijgi12020048.
28. Monteiro, J.; Sousa, N.; Natividade-Jesus, E.; Coutinho-Rodrigues, J. Benchmarking City Layouts—A Methodological Approach and an Accessibility Comparison between a Real City and the Garden City. *Sustainability* **2022**, *14*, 5029, doi:10.3390/su14095029.
29. Monteiro, J.; Para, M.; Sousa, N.; Natividade-Jesus, E.; Ostorero, C.; Coutinho-Rodrigues, J. Filling in the Spaces: Compactifying Cities towards Accessibility and Active Transport. *ISPRS International Journal of Geo-Information* **2023**, *12*, 120, doi:10.3390/ijgi12030120.
30. Deboosere, R.; El-Geneidy, A.M.; Levinson, D. Accessibility-Oriented Development. *Journal of Transport Geography* **2018**, *70*, 11–20, doi:10.1016/j.jtrangeo.2018.05.015.
31. Kompil, M.; Jacobs-Crisioni, C.; Dijkstra, L.; Lavalle, C. Mapping Accessibility to Generic Services in Europe: A Market-Potential Based Approach. *Sustainable Cities and Society* **2019**, *47*, 101372, doi:10.1016/j.scs.2018.11.047.
32. Bertolini, L.; le Clercq, F.; Kapoen, L. Sustainable Accessibility: A Conceptual Framework to Integrate Transport and Land Use Plan-Making. Two Test-Applications in the Netherlands and a Reflection on the Way Forward. *Transport Policy* **2005**, *12*, 207–220, doi:10.1016/j.tranpol.2005.01.006.
33. Shen, G.; Wang, Z.; Zhou, L.; Liu, Y.; Yan, X. Home-Based Locational Accessibility to Essential Urban Services: The Case of Wake County, North Carolina, USA. *Sustainability* **2020**, *12*, 9142, doi:10.3390/su12219142.
34. Owen, A.; Levinson, D.M. Modeling the Commute Mode Share of Transit Using Continuous Accessibility to Jobs. *Transportation Research Part A: Policy and Practice* **2015**, *74*, 110–122, doi:10.1016/j.tra.2015.02.002.
35. Birr, K. Mode Choice Modelling for Urban Areas. *Technical Transactions* **2018**, *Vol. 115, iss. 6*, doi:10.4467/2353737XCT.18.087.8692.
36. Avila-Palencia, I.; Int Panis, L.; Dons, E.; Gaupp-Berghausen, M.; Raser, E.; Götschi, T.; Gerike, R.; Brand, C.; de Nazelle, A.; Orjuela, J.P.; et al. The Effects of Transport Mode Use on Self-Perceived Health, Mental Health, and Social Contact Measures: A Cross-Sectional and Longitudinal Study. *Environment International* **2018**, *120*, 199–206, doi:10.1016/j.envint.2018.08.002.
37. Dogan, T.; Yang, Y.; Samaranayake, S.; Saraf, N. Urbano: A Tool to Promote Active Mobility Modeling and Amenity Analysis in Urban Design. *Technology|Architecture + Design* **2020**, *4*, 92–105, doi:10.1080/24751448.2020.1705716.
38. Scheepers, C.E.; Wendel-Vos, G.C.W.; van Kempen, E.E.M.M.; de Hollander, E.L.; van Wijnen, H.J.; Maas, J.; den Hertog, F.R.J.; Staatsen, B.A.M.; Stipdonk, H.L.; Int Panis, L.L.R.; et al. Perceived Accessibility Is an Important Factor in Transport Choice — Results from the AVENUE Project. *Journal of Transport & Health* **2016**, *3*, 96–106, doi:10.1016/j.jth.2016.01.003.
39. Sousa, N.; Natividade-Jesus, E.; Coutinho-Rodrigues, J. Bike-Index – um índice de acessibilidade velocípede recorrendo a programação em ambiente SIG. *Revista de Ciências da Computação* **2018**, *13*, 67–88, doi:10.34627/rcc.v13i0.151.
40. Kaza, N. Urban Form and Transportation Energy Consumption. *Energy Policy* **2020**, *136*, 111049, doi:10.1016/j.enpol.2019.111049.
41. Sun, L.; Zhang, T.; Liu, S.; Wang, K.; Rogers, T.; Yao, L.; Zhao, P. Reducing Energy Consumption and Pollution in the Urban Transportation Sector: A Review of Policies and Regulations in Beijing. *Journal of Cleaner Production* **2021**, *285*, 125339, doi:10.1016/j.jclepro.2020.125339.
42. RICKWOOD, P.; GLAZEBROOK, G.; SEARLE, G. Urban Structure and Energy—A Review. *Urban Policy and Research* **2008**, *26*, 57–81, doi:10.1080/08111140701629886.
43. 15-Minute City | Deloitte Global Available online: https://www.deloitte.com/global/en/Industries/government-public/perspectives/urban-future-with-a-purpose/15-minute-city.html (accessed on 21 February 2023).
44. Instituto Nacional de Estatistica, Censos 2011 Available online: https://censos.ine.pt/xportal/xmain?xpid=CENSOS&xpgid=censos2011_apresentacao (accessed on 21 February 2023).
45. Metro Mondego Available online: https://www.metromondego.pt/pt/home (accessed on 19 February 2023).
46. Energy Intensity of Passenger Transport Modes, 2018 – Charts – Data & Statistics Available online: https://www.iea.org/data-and-statistics/charts/energy-intensity-of-passenger-transport-modes-2018 (accessed on 12 January 2023).
47. Howard, E. *To-Morrow: A Peaceful Path to Real Reform*; Cambridge Library Collection - British and Irish History, 19th Century; Cambridge University Press: Cambridge, 2010; ISBN 978-1-108-02192-0.
48. Le Corbusier *The City of Tomorrow*; 1972; ISBN 978-0-262-62017-8.
49. Dittmar, H.; Ohland, G. *THE NEW TRANSIT TOWN: BEST PRACTICES IN TRANSIT-ORIENTED DEVELOPMENT*; 2004; ISBN 978-1-55963-117-4.
50. Neuman, M. The Compact City Fallacy. *Journal of Planning Education and Research* **2005**, *25*, 11–26, doi:10.1177/0739456X04270466.
51. Duany, A.; Speck, J.; Lydon, M. *The Smart Growth Manual*; McGraw Hill Professional, 2010; ISBN 978-0-07-137675-4.
52. Center for Applied Transect Studies Available online: https://transect.org/transect.html (accessed on 8 May 2023).
53. Pais, F.; Monteiro, J.; Sousa, N.; Coutinho-Rodrigues, J.; Natividade-Jesus, E. A Multicriteria Methodology for Maintenance Planning of Cycling Infrastructure. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability* **2022**, *175*, 248–264, doi:10.1680/jensu.21.00088.