Delineation of Traffic Analysis Zone for Public Transportation OD Matrix Estimation Based on Socio-spatial Practices

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Abstract

This paper aims to develop and validate an efficient method for delineation of public transit analysis zones (PTTAZ), particularly for origin-destination (OD) matrix prediction for transit operation planning. Existing methods have a problem in reflecting the level of spatial precision, travel characteristics, travel demand growth, access to transit stations, and most importantly, the direction of transit routes. This study proposes a new methodology to re-delineate existing traffic analysis zones (TAZ) to create PTTAZ in order to allocate travel demand to transit stops. We aim to achieve an accurate prediction of the OD matrix for public transportation (PT). The matrix should reflect the passenger accessibility in the socio-economic and socio-spatial characterization of PTTAZ and minimize intrazonal trips. The proposed methodology transforms TAZ-based to PTTAZ-based data with sequential steps through multiple statistical methods. In short, the generation of PTTAZ establishes homogeneous sub-zones representing the relationship between passenger flow, network structure, land use, population, socio-economic characteristics, and, most importantly, existing bus transit infrastructure. To validate the proposed scheme, we implement the framework for India's Vishakhapatnam bus network and compare the results with the household survey. The results show that the PTTAZ-based OD matrix represents a realistic scenario for PT demand.

Keywords: public transportation delineation; travel demand; traffic analysis zones; data allocation; empirical data

1 Introduction

The demand for public transport (PT) services is essential for any transport planning and operation management [Hol07]. Therefore, an accurate prediction model is essential. In general, the prediction framework begins with the generation of a zoning scheme (ZS) and represents the transportation network; the former is to represent user's demand, and the latter is to represent network supply and allocation of traffic flows on the network [Cui20]. ZS contains information on passenger trips and activities between origins and destinations. For decades, methodologies to estimate Origin-Destination (OD) matrices have been directly dependent on three main factors: (i) the scale of analyzing models (macroscopic, microscopic, or mesoscopic [Flü14]), (ii) demand prediction models (flow-based, trip-based, or activity-based [Bao15]), and (iii) availability of empirical, analytical or simulation data [Man20]. In all settings, the formation of OD on the traffic network has a crucial impact on the final output [Mar09; Cha02; Ort11]. In this regard, the notion of ZS plays a decisive role in generating the trip profile and the OD matrix. It represents a geographical unit linking spatial characteristics with the operating network [Fot91].

The most widely ZS used by authorities is known as traffic analysis zones (TAZ) [Mil21]. TAZ divides the study area into geographic units [McN07]. In practice, TAZ is defined as a geographic entity delineated by transport authorities to tabulate transportation statistics [USC20]. The research related to the TAZ scheme had different objectives over the past decades. The investigation of issues and challenges related to the definition and design of the ZS can be categorized into two main groups: (i) principles and (ii) techniques. In general, the zone integrity features are adapted to develop ZS specific for different transportation modes (e.g. private vehicles, trains, freights, metro, bicycles, and taxis [Sah20; Cha21; Mun19]). The aim of ZS for each transportation mode is to achieve a zoning structure able to represent a homogeneous distribution of socio-spatial characteristics (e.g. population, household, and employment), a homogeneous distribution of trips that are produced at each zone and attracted by other zones; while considering zone size, their compactness, overlapping and minimization of the proportion of intra-zonal trips [Dag80; You98].

Here, we present a summary of our literature review on ZS delineation methods. Note that a wide range of systematic zone delineation techniques has been explored in recent years, e.g. clustering and cell generation techniques [Mar09], graph theory [Ass06], mathematical programming [Shi05], and heuristic search methods [Ope77; Wan14a]. Furthermore, several authors investigated the impact of ZS on demand modeling [Den20], including the relationship between ZS and spatial factors and gaps that exist in delineation methods [Man19; Pan19]. The highlights of challenges related to the design and definition of TAZ that are addressed in the literature are as follows:

1. Examining the effects of network details and the size of TAZ on planning [Kap01].
2. Developing an algorithm that constructs ZS by aggregating the geocoded trip ends (origin and destination) into a cell grid [Mar07].

3. Developing a methodology with square grid-based boundaries (200 meters length) for TAZ delineation while reducing average intra-zonal trips [Mar09].

4. Defining a set of quality criteria for a general ZS and a hierarchical TAZ delineation algorithm [Mar10].

5. Analysing the aggregation effects of TAZ structures on the traffic assignment [Jeo12].

6. Investigating the aggregation level of zoning with calibrated gravity model [Cab16].

7. Subdividing TAZ into the service area by polygons created around the links using raster method [Hor01].

All the mentioned methods are implemented either for private cars or railway PT. We noticed that the implemented design scheme of TAZ on the bus transit passenger demand to estimate the OD matrix is either not fully investigated or ignored in most studies. Moreover, in small and medium-sized cities (SMCs)[1], buses have become a dominant transportation mode among PT modes [Mah19; Die19; Tiw21]. Therefore, the generation of public transport-based analysing zone (PTTAZ) should establish a relationship between passenger flow, network structure, land use, the population in SMCs, socio-economic characteristics, and, most importantly, existing bus transit infrastructure. However, our literature review shows that there are limited practical guidelines for PTTAZ generation as a tool to achieve accurate station-based OD matrices. This study aims to fill this research gap in ZS specific for PT operation and proposes a disaggregated passenger travel behavior prediction scheme. We propose to add a new set of zone integrity features into our delineation method. With new features, we are able to generate a station-based OD matrix considering (1) potential demand, (2) minimization of loss of intra-zonal trips, (3) accessibility of passengers to bus stations, and (4) dis-aggregation of spatial data subject to availability of transit routes, stations, and direction of routes.

2 Methodology

Figure 1 presents an overview of the proposed framework to generate PTTAZ. In the restructuring module, we first divide the TAZ area into smaller homogeneous zones (called sub-zones). We used a grid in this study based on [Mar09]. Second, characteristics of each TAZ are allocated to new sub-zones subject to spatial features of each TAZ. The heterogeneous centroids of TAZ are now converted to homogeneous centroids of subzones. Accordingly, each sub-zone is defined as a geographic unit [Mil99; Bov83]. Third, each bus station is set as a new traffic unit (i.e. PTTAZ). The size of the PTTAZ is interpreted in terms of passengers accessibility to transit stations [Poe15; Gut08; Kim07; Mur03; El-14], the cost of

[1] SMCs population is defined based on the size of considered country, e.g. for France, SMCs have population $\leq 100,000$ [Gro20], or Switzerland $\leq 50,000$ [Wag21] and on other continents, for India, $\leq$ four millions [Tiw11]

using transport services, and the travel cost that is taken to access a transit station [Mur98; Mav12].

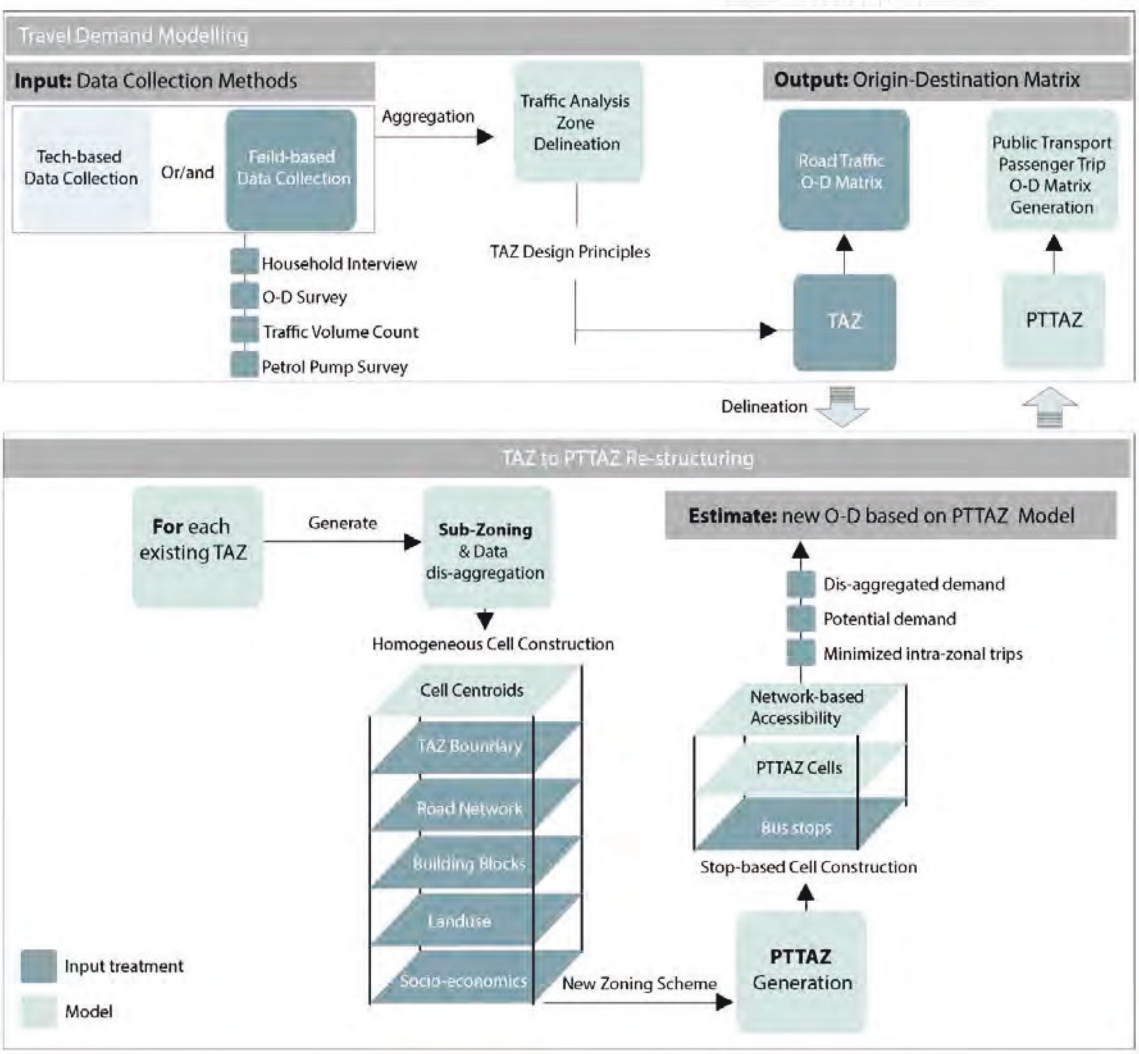

Figure 1: Public transport traffic analysis zone delineation.

The main contribution of this study is developing a new framework for predicting the OD matrix for bus transit networks based by introducing PTTAZ scheme to overcome the mentioned limitations of using TAZ scheme. In other words, the ultimate goal of the proposed framework is to transform the TAZ-based OD matrix into sub-zones and then create PTTAZ to predict the bus station-based OD matrix. The main steps of the methodology are listed below:

1. Identifying PTTAZ features based on Re-scaling TAZ with respect to PT stations.
    - Sub-zonning: TAZs are sub-zoned as 400 m^2 grid cells [Zha05; Mar09]; a size which has been recognized as the most acceptable distance for passengers who are willing to access PT by walking [Bib10].

- Spatial characteristics of zones and stations: To minimize the aggregation error caused by activity concentration at the centroid of each zone [Wan14b; Hor01], a new ZS is generated around each transit stop (i.e. PTTAZ) with 400 meters buffer around stop.
- Intra-zonal trips: While individual passengers are dis-aggregated within existing sub-zones, a certain number of passenger trips that are intra-zonal may not be captured [You98; Bha11]. By reducing the size of sub-zones, we can minimize intra-zonal trips.

2. Formulating PTTAZ with respect to TAZ scheme
   - To develop sub-zoning scheme, each grid cell's attribute is divided into its build up land use characteristics. Later, the land use criterion is used to decide which grid cell does not represent a relation with bus stations.
3. Demand allocation from TAZ to grid cells (sub-zones).
   - The demand is allocated from TAZ to grid cells as a function of the number of residential blocks, the area of each cell, and the average household size (see Figure 2).
   - Based on the stated preference survey (SPS) and HHS data, people using motorized travel modes who are willing to shift to bus service are also identified. Potential demand is then allocated based on the average trip length of people who are willing to shift, corresponding income level, and total travel time.
4. Inter-intra cellular evaluation and allocate demand from sub-zones to PTTAZ.
   - The walking distance of passengers from each cell's centroid to each station is measured for the entire network using the shortest path. The catchment area of entire stations is then evaluated through Euclidean and network-based walking distance.
   - For those grid cells under overlapped catchment areas, each cell is divided into sub-sections, the population density ratio of each sub-section is re-evaluated and demand is re-allocated to the nearest station.

3 Case Study

The Visakhapatnam Municipal Corporation area is considered the study area. A data set has been collected by a household survey [Aro17]. The city has a population of more than 1.73 million. The network is divided into 97 TAZs having a built-up area of 130 km^2. There are 52 bus routes operating on a daily basis in two directions. The most recent travel demand forecasting in the city is based on TAZ extracted from the mentioned household survey. Primary surveys (i.e. household interviews, traffic volume count, OD survey, and petrol pump

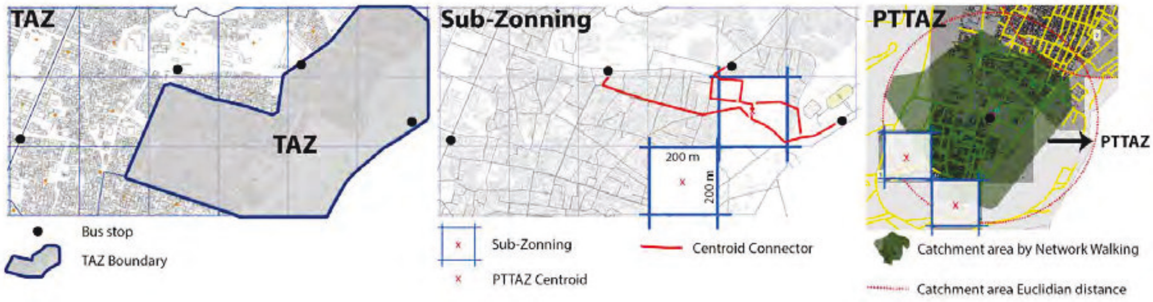

Figure 2: Partitioning of existing TAZ into cell grids (PTTAZ), centroid and centroid connectors.

survey) have been carried out to collect data on missing components in the secondary data (i.e. City Development Plan, Master Plan, Bus Route and Operations Data and Property Tax Data for individual households). In this study, we have used both data sets to generate PTTAZ.

4 Results and Discussion

Existing TAZ are sub-zoned into 19900 grid cells. The final numbers of cells after filtering land use constraints are 3328 cells. Using GPS, 137 bus stops are identified for urban area. Total of 101703 passengers are assigned to bus stops through the proposed model during morning peak hour. Access walking time that someone is forced to overcome to get to a transit stop is an important service performance measure and critical factor in PT operation [Mur01]. Based on the access walking time of passengers from their origin to their nearest transit stop, the effect of the proposed zoning scheme and quality of passenger travel demand distribution among transit stops can be validated. We used this validation technique by using observed data from household survey data and compared the observed average walking time to bus stop with the actual walking time from small grids PT based zone's centroid to bus stops. Table 1 shows values of average travel time (ATT) for both PTTAZ- and TAZ-based delineation methods with corresponding sample size of PT users within each TAZ and deviation of average walking time from existing traffic analysis zones data (driven from HHS).

5 Conclusions

The primary results show using PTTAZ scheme can help transportation planners to increase the accuracy of the bus demand prediction model. It is important to note that the delineation of the TAZ into PTTAZ is done through geospatial information and demand allocation. As a result, the potential transit users' preferences are incorporated into the final estimate of the PTTAZ demand matrix, and intra-zonal transit trips are minimized, resulting in better transit demand estimates on the bus stop level. It is worth mentioning that creating small sub-

Table 1: Values of average walking time to transit stop for TAZ and PTTAZ schemes.

TAZ ID	TAZ-ATT	Sample Size	PTTAZ-ATT	Deviation	TAZ ID	Sample Size	TAZ-ATT	PTTAZ-ATT	Deviation	TAZ ID	Sample Size	TAZ-ATT	PTTAZ-ATT	Deviation
1	12.2	16	12.1	-0.6	**34**	55	10.5	10.6	0.7	**67**	0	0.0	0.0	0.0
2	10.0	5	11.4	13.7	**35**	65	17.0	13.4	-21.1	**68**	157	13.5	15.1	11.8
3	14.3	28	13.3	-6.8	**36**	59	11.5	11.0	-4.3	**69**	86	9.0	6.6	-26.4
4	14.0	103	13.6	-2.7	**37**	0	0.0	0.0	0.0	**70**	88	4.7	7.7	62.9
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28	15.6	77	13.9	-11.0	**61**	7	0.0	0.0	0.0	.	.	.	.	.
29	0.0	0	0.0	0.0	**62**	116	14.6	14.7	0.5	.	.	.	.	.
30	17.6	185	14.2	-19.0	**63**	0	0.0	0.0	0.0	.	.	.	.	.
31	14.1	49	11.2	-20.2	**64**	82	10.4	9.9	-4.8	.	.	.	.	.
32	0.0	0	0.0	0.0	**65**	82	10.4	9.9	-4.8	.	.	.	.	.
33	19.0	4	17.0	-10.3	**66**	141	34.2	27.9	-18.3	**97**	0	0.0	0.0	0.0

zones and disaggregating them through the proposed PTTAZ scheme helps to maximize the usage of effective design criteria. The procedure was tested using data from Vishakhapatnam city, India. We are currently analyzing the validation results to provide more insights about deploying the PTTAZ scheme in the OD prediction model. We intend to consider the bus services to allocate passengers to PTTAZs, based on the direction of transit routes and predict passengers routes and bus loads during the peak hour.

References

[Aro17] A. Arora, R. Gadepalli, P. Sharawat, and A. Vaid: *Low Carbon Comprehensive Mobility Plan - Visakhapatnam*. UNEP DTU Partnership, Technical University, Denmark, Nov. 2017. ISBN: 978-8-79-313025-8.

[Ass06] R. M. Assunção, M. C. Neves, G. Câmara, and C. D. C. Freitas: “Efficient regionalization techniques for socio-economic geographical units using minimum spanning trees”. In: *International Journal of Geographical Information Science* 20.7 (2006), pages 797–811. ISSN: 1365-8824. DOI: 10.1080/13658810600665111.

[Bao15] Q. Bao, Y. Shen, L. Creemers, B. Kochan, T. Bellemans, D. Janssens, and G. Wets: “Investigating the Minimum Size of Study Area for an Activity-Based Travel Demand Forecasting Model”. In: *Mathematical Problems in Engineering* 2015 (Mar. 2015), pages 1–9. ISSN: 1563-5147. DOI: 10.1155/2015/162632.

[Bha11] B. P. Bhatta and O. I. Larsen: “Are intrazonal trips ignorable”. In: *Transport Policy* 18 (2011), pages 13–22. ISSN: 0967-070X.

[Bib10] S. Biba, K. M. Curtin, and G. Manca: “A new method for determining the population with walking access to transit”. In: *International Journal of Geographical*

Information Science 24.3 (2010), pages 347–364. DOI: 10.1080/13658810802646679.

[Bov83] P. H. L. Bovy and G. R. M. Jansen: “Network Aggregation Effects upon Equilibrium Assignment Outcomes: An Empirical Investigation”. In: *Transportation Science* 17.3 (1983), pages 240–262. ISSN: 0041-1655. URL: http://www.jstor.org/stable/25768096 (visited on 03/20/2023).

[Cab16] J. Cabrera Delgado and P. Bonnel: “Level of aggregation of zoning and temporal transferability of the gravity distribution model: The case of Lyon”. In: *Journal of Transport Geography* 51 (2016), pages 17–26. ISSN: 0966-6923. DOI: 10.1016/j.jtrangeo.2015.1.

[Cha02] K.-T. Chang, Z. Khatib, and Y. Ou: “Effects of Zoning Structure and Network Detail on Traffic Demand Modeling”. In: *Environment and Planning B* 29.1 (Feb. 2002), pages 37–52. DOI: 10.1068/b2742.

[Cha21] A. Chandra, M. Sharath, A. Pani, and P. K. Sahu: “A multi-objective genetic algorithm approach to design optimal zoning systems for freight transportation planning”. In: *Journal of Transport Geography* 92 (2021). ISSN: 0966-6923. DOI: 10.1016/j.jtrangeo.2021.103037.

[Cui20] Y. Cui and R. Moeckel: “Defining the resolution of a network for transportation analyses: A new methodology and algorithm”. In: *Environment and Planning B: Urban Analytics and City Science* 47.9 (2020), pages 1639–1654. DOI: 10.1177/2399808319834309.

[Dag80] C. F. Daganzo: “An equilibrium algorithm for the spatial aggregation problem of traffic assignment”. In: *Transportation Research Part B: Methodological* 14.3 (1980), pages 221–228. ISSN: 0191-2615. DOI: 10.1016/0191-2615(80)90001-6.

[Den20] J. Deng, X. Chen, and L. Ma: “Analysis of the Impact of Traffic Analysis Zones Division on Traffic Assignment”. In: *20th COTA International Conference of Transportation*. 2020, pages 2526–2537. DOI: 10.1061/9780784482933.218.

[Die19] R. Diemer and F. Dittrich: *Transport in the european union current trends and issues*. Technical report. 2019. URL: https://ec.europa.eu/transport/sites/default/files/2019-transport-in-the-eu-current-trends-and-issues.pdf.

[El-14] A. El-Geneidy, M. Grimsrud, R. Wasfi, P. Tétreault, and J. Surprenant-Legault: “New evidence on walking distances to transit stops: identifying redundancies and gaps using variable service areas”. In: *Transportation* 41.1 (Jan. 2014), pages 193–210. ISSN: 1572-9435. DOI: 10.1007/s11116-013-9508-z.

[Flü14] S. Flügel, G. Flötteröd, C. K. Kwong, and C. Steinsland: *Evaluation of Methods for Calculating Traffic Assignment and Travel Times in Congested Urban Areas with Strategic Transport Models*. Institute of Transport Economics, Norwegian Centre for Transport Research, 2014. ISBN: 978-82-480-1574-1.

[Fot91] A. S. Fotheringham and D. W. S. Wong: "The Modifiable Areal Unit Problem in Multivariate Statistical Analysis". In: *Environment and Planning A: Economy and Space* 23.7 (1991), pages 1025–1044. DOI: 10.1068/a231025.

[Gro20] M. Gros-Balthazard and M. Talandier: "Cooperation, Proximity, and Social Innovation: Three Ingredients for Industrial Medium-Sized Towns' Renewal?" In: *Urban Science* 4.2 (2020). ISSN: 2413-8851. DOI: 10.3390/urbansci4020015.

[Gut08] J. Gutiérrez and J. C. García-Palomares: "Distance-Measure Impacts on the Calculation of Transport Service Areas Using GIS". In: *Environment and Planning B: Planning and Design* 35.3 (2008), pages 480–503. DOI: 10.1068/b33043.

[Hol07] J. Holmgren: "Meta-analysis of public transport demand". In: *Transportation Research Part A: Policy and Practice* 41.10 (2007), pages 1021–1035. URL: https://EconPapers.repec.org/RePEc:eee:transa:v:41:y:2007:i:10:p:1021-1035.

[Hor01] A. J. Horowitz: "Computational Issues in Increasing Spatial Precision of Traffic Assignments". In: *Transportation Research Record* 1777.1 (2001), pages 68–74. ISSN: 0361-1981. DOI: 10.3141/1777-07.

[Jeo12] J.-H. Jeon, S.-Y. Kho, J. J. Park, and D.-K. Kim: "Effects of Spatial Aggregation Level on an Urban Transportation Planning Model". In: *KSCE Journal of Civil Engineering* 16.5 (2012), pages 835–844. ISSN: 1226-7988.

[Kap01] B. Kaplan, L. Englisher, and M. Warner: *Actual Versus Forecast Ridership on Metrolink in St. Clair County, Illinois*. Technical report. 2001. URL: https://www.trb.org/publications/circulars/ec058/03_03_Kaplan.pdf.

[Kim07] T. J. Kimpel, K. J. Dueker, and A. El-geneidy: "Using GIS to Measure the Effect of Overlapping Service Areas on Passenger Boardings at Bus Stops". In: *URISA Journal* 19 (2007), pages 5–11. ISSN: 2378-6000.

[Mah19] S. H. Mahdavi Moghaddam, K. R. Rao, G. Tiwari, and P. Biyani: "Simultaneous bus transit route network and frequency setting search algorithm". In: *Journal of Transportation Engineering, Part A: Systems* 145.4 (2019). ISSN: 2473-2893. DOI: 10.1061/JTEPBS.0000229.

[Man19] O. Manout and P. Bonnel: "The impact of ignoring intrazonal trips in assignment models: a stochastic approach". In: *Transportation* 46 (Dec. 2019), pages 2397–2417. ISSN: 1572-9435. DOI: 10.1007/s11116-018-9951-y.

[Man20] P. Manser, H. Becker, S. Hörl, and K. W. Axhausen: "Designing a large-scale public transport network using agent-based microsimulation". In: *Transportation Research Part A: Policy and Practice* 137 (2020), pages 1–15. ISSN: 0965-8564. DOI: 10.1016/j.tra.2020.04.011.

[Mar07] L. M. Martínez, J. M. Viegas, and E. A. Silva: "Zoning Decisions in Transport Planning and Their Impact on the Precision of Results". In: *Transportation Research Record* 1994.1 (2007), pages 58–65. ISSN: 0361-1981. DOI: 10.3141/1994-08.

[Mar09] L. M. Martinez, J. M. Viegas, and E. A. Silva: "A traffic analysis zone definition: a new methodology and algorithm". In: *Transportation* 36 (2009), pages 581–599. ISSN: 1572-9435.

[Mar10] L. M. Martínez, A. Dupont-Kieffer, and J. M. Viegas: "An integrated application of zoning for mobility analysis and planning: the case of Paris Region". In: *Proceedings of the World Conference on Transport Research*. Lisbonne,Portugal, July 2010. URL: https://hal.archives-ouvertes.fr/hal-00614973.

[Mav12] S. Mavoa, K. Witten, T. McCreanor, and D. O'Sullivan: "GIS based destination accessibility via public transit and walking in Auckland, New Zealand". In: *Journal of transport geography* 20.1 (2012), pages 15–22. ISSN: 0966-6923. DOI: 10.1016/j.jtrangeo.2011.10.001.

[McN07] M. G. McNally: "Handbook of Transport Modelling". In: edited by D. A. Hensher and K. J. Button. Volume 1. Bingley: Emerald Group Publishing Limited, 2007. Chapter The Four-Step Model, pages 35–53. ISBN: 978-0-08-045376-7. DOI: 10.1108/9780857245670-003.

[Mil21] E. J. Miller: *Traffic Analysis Zone Definition: Issues & Guidance*. Technical report. 2021. URL: https://tmg.utoronto.ca/files/Reports/Traffic-Zone-Guidance_March-2021_Final.pdf.

[Mil99] H. J. Miller: "Measuring space-time accessibility benefits within transportation networks: Basic theory and computational procedures". In: *Geographical analysis* 31.1 (1999), pages 187–212. ISSN: 1538-4632.

[Mun19] W. Mungthanya, S. Phithakkitnukoon, M. G. Demissie, L. Kattan, M. Veloso, C. Bento, and C. Ratti: "Constructing time-dependent origin-destination matrices with adaptive zoning scheme and measuring their similarities with taxi trajectory data". In: *IEEE Access* 7 (2019), pages 77723–77737. ISSN: 2169-3536. DOI: 10.1109/ACCESS.2019.2922210.

[Mur01] A. T. Murray: "Strategic analysis of public transport coverage". In: *Socio-Econo-mic Planning Sciences* 35.3 (2001), pages 175–188. ISSN: 1873-6041.

[Mur03] A. T. Murray and X. Wu: "Accessibility tradeoffs in public transit planning". In: *Journal of Geographical Systems* 5 (2003), pages 93–107. ISSN: 1435-5930. DOI: 10.1007/s101090300105.

[Mur98] A. T. MURRAY, R. DAVIS, R. J. STIMSON, and L. FERREIRA: "Public transportation access". In: *Transportation Research Part D: Transport and Environment* 3.5 (1998), pages 319–328. ISSN: 1361-9209.

[Ope77] S. OPENSHAW: "A geographical solution to scale and aggregation problems in region-building, partitioning and spatial modelling". In: *Transactions of the institute of british geographers* (1977), pages 459–472. ISSN: 0020-2754.

[Ort11] J. d. D. ORTUZAR and L. G. WILLUMSEN: "Activity Based Models". In: *Modelling Transport*. John Wiley & Sons, Ltd, 2011. Chapter 14, pages 473–487. ISBN: 978-1-11-999330-8. DOI: 10.1002/9781119993308.ch14.

[Pan19] A. PANI, P. K. SAHU, A. CHANDRA, and A. K. SARKAR: "Assessing the extent of modifiable areal unit problem in modelling freight (trip) generation: Relationship between zone design and model estimation results". In: *Journal of Transport Geography* 80 (2019). ISSN: 0966-6923. DOI: 10.1016/j.jtrangeo.2019.102524.

[Poe15] H. POELMAN and L. DIJKSTRA: *Measuring access to public transport in European cities*. Technical report. 2015. URL: https://ec.europa.eu/regional_policy/sources/work/2015_01_publ_transp.pdf.

[Sah20] P. K. SAHU, A. CHANDRA, A. PANI, and B. B. MAJUMDAR: "Designing freight traffic analysis zones for metropolitan areas: identification of optimal scale for macro-level freight travel analysis". In: *Transportation Planning and Technology* 43.6 (2020), pages 620–637. ISSN: 1029-0354. DOI: 10.1080/03081060.2020.1780711.

[Shi05] T. SHIRABE: "A model of contiguity for spatial unit allocation". In: *Geographical Analysis* 37.1 (2005), pages 2–16. ISSN: 1538-4632. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1538-4632.2005.00605.x.

[Tiw11] G. TIWARI: "Key mobility challenges in Indian cities". In: *International Transport Forum Discussion Papers*. 2011/18. 2011. DOI: 10.1787/5kg9mq4m1gwl-en.

[Tiw21] G. TIWARI and C. PHILLIP: "Development of public transport systems in small cities: A roadmap for achieving Emerging Technologies development goal indicator 11.2". In: *IATSS Research* 45.1 (2021), pages 31–38. ISSN: 3861-112. DOI: 10.1016/j.iatssr.2021.02.002.

[USC20] *MAF/TIGER feature class code definitions*. Technical report. 2020. URL: https://www2.census.gov/geo/pdfs/reference/mtfccs2020.pdf.

[Wag21] M. WAGNER and A. GROWE: "Research on small and medium-sized towns: Framing a new field of inquiry". In: *World* 2.1 (2021), pages 105–126. ISSN: 2673-4060. DOI: 10.3390/world2010008.

[Wan14a] L. Wang, J. Tang, X. Fei, and M. Gong: “A mixed integer programming formulation and solution for traffic analysis zone delineation considering zone amount decision”. In: *Information Sciences* 280 (2014), pages 322–337. ISSN: 0020-0255.

[Wan14b] S. Wang, L. Sun, J. Rong, and Z. Yang: “Transit traffic analysis zone delineating method based on Thiessen polygon”. In: *Sustainability* 6.4 (2014), pages 1821–1832. ISSN: 2071-1050.

[You98] J. You, Z. Nedović-Budić, and T. J. Kim: “A GIS-based traffic analysis zone design: implementation and evaluation”. In: *Transportation Planning and Technology* 21.1-2 (1998), pages 69–91. ISSN: 1029-0354.

[Zha05] M. Zhang and N. Kukadia: “Metrics of urban form and the modifiable areal unit problem”. In: *Transportation Research Record* 1902.1 (2005), pages 71–79. ISSN: 0361-1981.

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