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Delineation of traffic analysis zone for public transportation OD matrix estimation based on socio-spatial practices

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SHORT SUMMARY

This paper aims to develop and validate an efficient method for delineation of public transit analysis zones (PT-TAZ), 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 intra-zonal 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 (Holmgren, 2007). 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 (Cui and Moeckel, 2020). 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 (Alisoltani et al., 2020), microscopic (Ameli et al., 2022b), or mesoscopic (Flügel et al., 2014)), (ii) demand prediction models (flow-based Ameli et al. (2022a), trip-based (Alisoltani et al., 2019b), or activity-based (Bao et al., 2015)), and (iii) availability of empirical, analytical or simulation data (Manser et al., 2020; Ameli et al., 2021). In all settings, the formation of OD on the traffic network has a crucial impact on the final output (Martínez et al., 2009; Chang et al., 2002; Ortuzar and Willumsen, 2011; Alisoltani et al., 2019a). 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 (Fotheringham and Wong, 1991).

The most widely ZS used by authorities is known as traffic analysis zones (TAZ) (Miller, 2021). TAZ divides the study area into geographic units (Hensher and Button, 2007). In practice, TAZ is defined as a geographic entity delineated by transport authorities to tabulate transportation statistics (U.S.Census.Bureau, 2020). The research related

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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 (Sahu et al., 2020; Chandra et al., 2021; Mungthanya et al., 2019)). 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 (Daganzo, 1980; You et al., 1998).

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 (Martínez et al., 2009; Alisoltani et al., 2022), graph theory (Assuncao et al., 2006), mathematical programming (Shirabe, 2005), and heuristic search methods (Openshaw, 1977; Wang et al., 2014a). Furthermore, several authors investigated the impact of ZS on demand modeling (Deng et al., 2020), including the relationship between ZS and spatial factors and gaps that exist in delineation methods (Manout and Bonnel, 2019; Pani et al., 2019). 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 (Kaplan et al., 2001).
2. Developing an algorithm that constructs ZS by aggregating the geocoded trip ends (origin and destination) into a cell grid (Martinez et al., 2007).
3. Developing a methodology with square grid-based boundaries (200 meters length) for TAZ delineation while reducing average intra-zonal trips (Martínez et al., 2009).
4. Defining a set of quality criteria for a general ZS and a hierarchical TAZ delineation algorithm (Martinez et al., 2010).
5. Analysing the aggregation effects of TAZ structures on the traffic assignment (Jeon et al., 2012).
6. Investigating the aggregation level of zoning with calibrated gravity model (Cabrera Delgado and Bonnel, 2016).
7. Subdividing TAZ into the service area by polygons created around the links using raster method (Horowitz, 2001).

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 (Moghaddam et al., 2019; Diemer and Dittrich, 2019; Tiwari and Phillip, 2021). 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 dis-aggregated 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 re-structuring module, we first divide the TAZ area into smaller homogeneous zones (called sub-zones). We used a grid in this study based on (Martínez et al., 2009). Second, characteristics of each TAZ are allocated to new sub-zones subject to spatial

¹SMCs population is defined based on the size of considered country, e.g., for France, SMCs have population $\leq 100,000$ (Gros-Balthazard and Talandier, 2020), or Switzerland $\leq 50,000$ (Wagner and Growe, 2021) and on other continents, for India, \leq four millions (Tiwari, 2011)

features of each TAZ. The heterogeneous centroids of TAZ are now converted to homogeneous centroids of sub-zones. Accordingly, each sub-zone is defined as a geographic unit (Miller, 1999; Bovy and Jansen, 1983). 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 (Poelman and Dijkstra, 2015; Gutierrez and Garcia-Palomares, 2008; Kimpel et al., 2007; Murray and Wu, 2003; El-Geneidy et al., 2014), the cost of using transport services, and the travel cost that is taken to access a transit station (Murray et al., 1998; Mavoa et al., 2012).

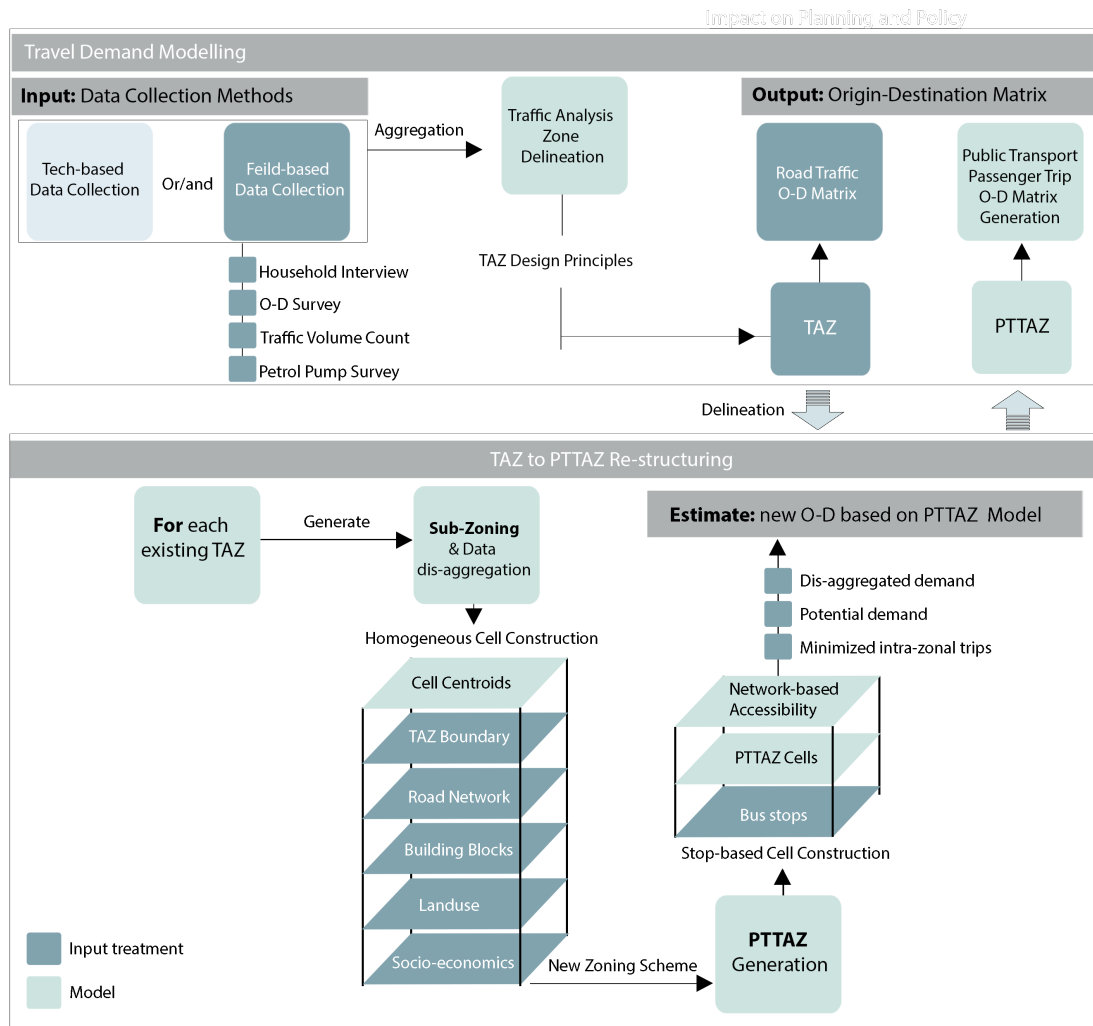


Figure 1: Public Transport Traffic Analysis Zone Delineation

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-zoning*: TAZs are sub-zoned as 400 m² grid cells (Zhang and Kukadia, 2005; Martínez et al., 2009); a size which has been recognized as the most acceptable distance for passengers who are willing to access PT by walking (Biba et al., 2010).

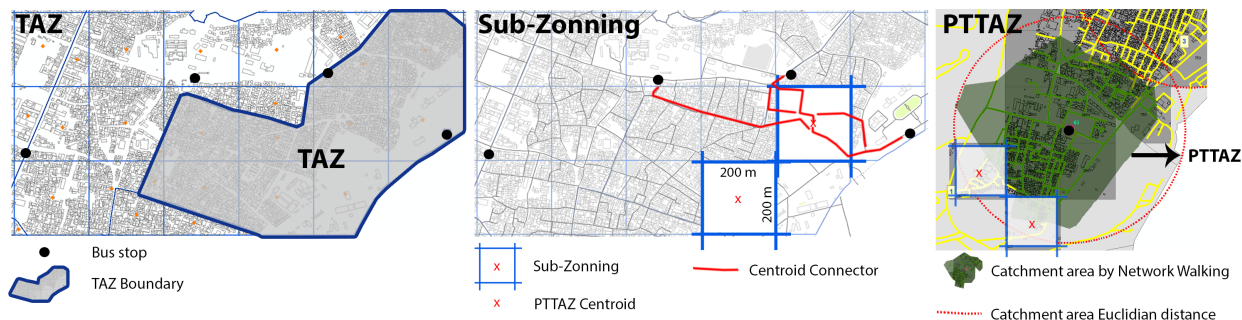


Figure 2: Partitioning of existing TAZ into cell grids (PTTAZ), centroid and centroid connectors.

- *Spatial characteristics of zones and stations:* To minimize the aggregation error caused by activity concentration at the centroid of each zone (Wang et al., 2014b; Horowitz, 2001), 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 (You et al., 1998; Bhatta and Larsen, 2011). 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 (Arora et al., 2017). 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 km². 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 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 (Murray, 2001). 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).

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
.
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	21	8.3	9.4	13.3	.	.	.	.	.
33	19.0	4	17.0	-10.3	66	141	34.2	27.9	-18.3	97	0	0.0	0.0	0.0

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-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

- Alisoltani, N., Ameli, M., Zargayouna, M., Leclercq, L., 2022. Space-time clustering-based method to optimize shareability in real-time ride-sharing. *Plos one* 17 (1), e0262499.
- Alisoltani, N., Zargayouna, M., Leclercq, L., 2019a. Data-oriented approach for the dial-a-ride problem. In: 2019 IEEE/ACS 16th International Conference on Computer Systems and Applications (AICCSA). IEEE, pp. 1–6.
- Alisoltani, N., Zargayouna, M., Leclercq, L., 2019b. A multi-agent system for real-time ride sharing in congested networks. In: *Agents and Multi-agent Systems: Technologies and Applications 2019: 13th KES International Conference, KES-AMSTA-2019 St. Julians, Malta, June 2019 Proceedings*. Springer, pp. 333–342.
- Alisoltani, N., Zargayouna, M., Leclercq, L., 2020. Real-time autonomous taxi service: An agent-based simulation. In: *Agents and Multi-Agent Systems: Technologies and Applications 2020: 14th KES International Conference, KES-AMSTA 2020, June 2020 Proceedings*. Springer, pp. 199–207.
- Ameli, M., Faradonbeh, M. S. S., Lebacque, J.-P., Abouee-Mehrizi, H., Leclercq, L., 2022a. Departure time choice models in urban transportation systems based on mean field games. *Transportation Science* 56 (6), 1483–1504.
- Ameli, M., Lebacque, J.-P., Leclercq, L., 2021. Computational methods for calculating multimodal multiclass traffic network equilibrium: Simulation benchmark on a large-scale test case. *Journal of Advanced Transportation* 2021, 1–17.

- Ameli, M., Lebacque, J. P., Leclercq, L., 2022b. Evolution of multimodal final user equilibrium considering public transport network design history. *Transportmetrica B: Transport Dynamics* 10 (1), 923–953.
- Arora, A., et al., 2017. Low-carbon comprehensive mobility plan: Vishakhapatnam. Low Carbon Transport in India Project.
- Assuncao, R. M., Neves, M. C., Camara, G., Freitas, C. D. C., 2006. Efficient regionalization techniques for socio-economic geographical units using minimum spanning trees. *International Journal of Geographical Information Science* 20 (7), 797–811.
URL <https://doi.org/10.1080/13658810600665111>
- Bao, Q., Shen, Y., Creemers, L., Kochan, B., Bellemans, T., Janssens, D., Wets, G., 2015. Investigating the minimum size of study area for an activity-based travel demand forecasting mode. *Mathematical Problems in Engineering*, 9.
- Bhatta, B. P., Larsen, O. I., 2011. Are intrazonal trips ignorable? *Transport policy* 18 (1), 13–22.
- Biba, S., Curtin, K. M., Manca, G., 2010. A new method for determining the population with walking access to transit. *International Journal of Geographical Information Science* 24 (3), 347–364.
- Bovy, P., Jansen, G., 1983. Network aggregation effects upon equilibrium assignment outcomes: An empirical investigation. *Transportation Science* 17 (3), 240–262.
- Cabrera Delgado, J., Bonnel, P., 2016. Level of aggregation of zoning and temporal transferability of the gravity distribution model: The case of Lyon. *Journal of Transport Geography* 51, 17–26.
URL <https://www.sciencedirect.com/science/article/pii/S0966692315001982>
- Chandra, A., Sharath, M., Pani, A., Sahu, P. K., 2021. A multi-objective genetic algorithm approach to design optimal zoning systems for freight transportation planning. *Journal of Transport Geography* 92, 103037.
URL <https://www.sciencedirect.com/science/article/pii/S0966692321000909>
- Chang, K.-t., Khatib, Z., Ou, Y., 2002. Effects of zoning structure and network detail on traffic demand modeling. *Environment and Planning B: Planning and Design* 29 (1), 37–52.
- Cui, Y., Moeckel, R., 2020. Defining the resolution of a network for transportation analyses: A new methodology and algorithm. *Environment and Planning B: Urban Analytics and City Science* 47 (9), 1639–1654.
URL <https://doi.org/10.1177/2399808319834309>
- Daganzo, C. F., 1980. An equilibrium algorithm for the spatial aggregation problem of traffic assignment. *Transportation Research Part B: Methodological* 14 (3), 221–228.
- Deng, J., Chen, X., Ma, L., 2020. Analysis of the Impact of Traffic Analysis Zones Division on Traffic Assignment. pp. 2526–2537.
URL <https://ascelibrary.org/doi/abs/10.1061/9780784482933.218>
- Diemer, R., Dittrich, F., 2019. Transport in the European Union current trends and issues. Tech. rep., European Commission, Directorate-General Mobility and Transport, Brussels.
URL <https://ec.europa.eu/transport/sites/default/files/2019-transport-in-the-eu-current-trends-and-issues.pdf>
- El-Geneidy, A., Grimsrud, M., Wasfi, R., Tetreault, P., Surprenant-Legault, J., 2014. New evidence on walking distances to transit stops: identifying redundancies and gaps using variable service areas. *Transportation* 41 (1), 193–210.
URL <https://doi.org/10.1007/s11116-013-9508-z>
- Flügel, S., Flötteröd, G., Kwong, C. K., Steinsland, C., 2014. Evaluation of methods for calculating traffic assignment and travel times in congested urban areas with strategic transport models. Tech. rep., The Norwegian Public Roads Administration.
URL <https://www.toi.no/getfile.php?mmfileid=38655>
- Fotheringham, A. S., Wong, D. W. S., 1991. The modifiable areal unit problem in multivariate statistical analysis. *Environment and Planning A: Economy and Space* 23 (7), 1025–1044.
URL <https://doi.org/10.1068/a231025>
- Gros-Balthazard, M., Talandier, M., Apr. 2020. Cooperation, Proximity, and Social Innovation: Three Ingredients for Industrial Medium-Sized Towns' Renewal? *Urban Science* 4 (2), 1–21.
URL <https://halshs.archives-ouvertes.fr/halshs-02571601>
- Gutierrez, J., Garcia-Palomares, J. C., 2008. Distance-measure impacts on the calculation of transport service areas using GIS. *Environment and Planning B: Planning and Design* 35 (3), 480–503.
URL <https://doi.org/10.1068/b33043>
- Hensher, D. A., Button, K. J., 2007. *Handbook of Transport Modelling: The Four-Step Model*. Vol. 61.
- Holmgren, J., 2007. Meta-analysis of public transport demand. *Transportation Research Part A: Policy and Practice* 41 (10), 1021–1035.
- Horowitz, A. J., 2001. Computational issues in increasing spatial precision of traffic assignments. *Transportation Research Record* 1777 (1), 68–74.
- Jeon, J.-H., Kho, S.-Y., Park, J. J., Kim, D.-K., 2012. Effects of spatial aggregation level on an urban transportation planning model. *KSCE Journal of Civil Engineering* 16 (5), 835–844.
- Kaplan, B., English, L., Warner, M., 2001. Actual versus forecast ridership on metrolink in St. Clair County, Illinois.
- Kimpel, T. J., Dueker, K. J., El-Geneidy, A. M., 2007. Using GIS to measure the effect of overlapping service areas on passenger boardings at bus stops. *Urban and Regional Information Systems Association Journal* 19 (1).
- Manout, O., Bonnel, P., 2019. The impact of ignoring intrazonal trips in assignment models: a stochastic approach. *Transportation* 46 (6), 2397–2417.
URL <https://doi.org/10.1007/s11116-018-9951-y>
- Manser, P., Becker, H., Hörl, S., Axhausen, K. W., 2020. Designing a large-scale public transport network using agent-based microsimulation. *Transportation Research Part A: Policy and Practice* 137, 1–15.
- Martinez, L. M., Dupont-Kieffer, A., Viegas, J. M., Jul. 2010. An integrated application of zoning for mobility analysis and planning: the case of Paris Region. In: *on Transport Research Society*, W. C. (Ed.), 12th World Conference on Transport Research. Lisbonne, Portugal, p. 25p.
URL <https://hal.archives-ouvertes.fr/hal-00614973>
- Martinez, L. M., Viegas, J. M., Silva, E. A., 2007. Zoning decisions in transport planning and their impact on the precision of results. *Transportation Research Record* 1994 (1), 58–65.

- URL <https://doi.org/10.3141/1994-08>
- Martínez, L. M., Viegas, J. M., Silva, E. A., 2009. A traffic analysis zone definition: a new methodology and algorithm. *Transportation* 36 (5), 581–599.
- Mavoa, S., Witten, K., McCreanor, T., O’Sullivan, D., 2012. Gis based destination accessibility via public transit and walking in auckland, new zealand. *Journal of Transport Geography* 20 (1), 15–22, special Section On Child & Youth Mobility.
URL <https://www.sciencedirect.com/science/article/pii/S0966692311001529>
- Miller, E. J., 2021. Traffic analysis zone definition: Issues & guidance.
- Miller, H. J., 1999. Measuring space-time accessibility benefits within transportation networks: Basic theory and computational procedures. *Geographical analysis* 31 (1), 187–212.
- Moghaddam, S. M. H. M., Rao, K. R., Tiwari, G., Biyani, P., 2019. Simultaneous bus transit route network and frequency setting search algorithm. *Journal of Transportation Engineering, Part A: Systems* 145 (4), 04019011.
URL <https://ascelibrary.org/doi/abs/10.1061/JTEPBS.0000229>
- Munthanya, W., Phithakkitmukoon, S., Demissie, M. G., Kattan, L., Veloso, M., Bento, C., Ratti, C., 2019. Constructing time-dependent origin-destination matrices with adaptive zoning scheme and measuring their similarities with taxi trajectory data. *IEEE Access* 7, 77723–77737.
- Murray, A. T., 2001. Strategic analysis of public transport coverage. *Socio-Economic Planning Sciences* 35 (3), 175–188.
- Murray, A. T., Davis, R., Stimson, R. J., Ferreira, L., 1998. Public transportation access. *Transportation Research Part D: Transport and Environment* 3 (5), 319–328.
- Murray, A. T., Wu, X., 2003. Accessibility tradeoffs in public transit planning. *Journal of Geographical Systems* 5, 93–107.
URL <https://doi.org/10.1007/s101090300105>
- Openshaw, S., 1977. A geographical solution to scale and aggregation problems in region-building, partitioning and spatial modelling. *Transactions of the institute of british geographers*, 459–472.
- Ortuzar, J. d. D., Willumsen, L. G., 2011. John Wiley & Sons, Ltd.
URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119993308.ch14>
- Pani, A., Sahu, P. K., Chandra, A., Sarkar, A. K., 2019. Assessing the extent of modifiable areal unit problem in modelling freight (trip) generation: Relationship between zone design and model estimation results. *Journal of Transport Geography* 80, 102524.
URL <https://www.sciencedirect.com/science/article/pii/S0966692319302455>
- Poelman, H., Dijkstra, L., 2015. Measuring access to public transport in european cities. Tech. rep., European Commission; Regional Working Paper.
URL https://ec.europa.eu/regional_policy/sources/docgener/work/2015_01_publ_transp.pdf
- Sahu, P. K., Chandra, A., Pani, A., Majumdar, B. B., 2020. Designing freight traffic analysis zones for metropolitan areas: identification of optimal scale for macro-level freight travel analysis. *Transportation Planning and Technology* 43 (6), 620–637.
URL <https://doi.org/10.1080/03081060.2020.1780711>
- Shirabe, T., 2005. A model of contiguity for spatial unit allocation. *Geographical Analysis* 37 (1), 2–16.
URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1538-4632.2005.00605.x>
- Tiwari, G., 2011. Key mobility challenges in indian cities. *International Transport Forum Discussion Papers* 18, Organisation for Economic Cooperation and Development (OECD), International Transport Forum, Paris, Paris.
URL <https://doi.org/10.1787/5kg9mq4m1gw1-en>
- Tiwari, G., Phillip, C., 2021. Development of public transport systems in small cities: A roadmap for achieving sustainable development goal indicator 11.2. *IATSS Research* 45 (1), 31–38.
URL <https://www.sciencedirect.com/science/article/pii/S038611221000078>
- U.S.Census.Bureau, 2020. Maf/tiger feature class code definitions. Tech. rep., United States Census Bureau.
URL <https://www2.census.gov/geo/pdfs/reference/mtfccs2020.pdf>
- Wagner, M., Growe, A., 2021. Research on small and medium-sized towns: Framing a new field of inquiry. *World* 2 (1), 105–126.
URL <https://www.mdpi.com/2673-4060/2/1/8>
- Wang, L., Tang, J., Fei, X., Gong, M., 2014a. A mixed integer programming formulation and solution for traffic analysis zone delineation considering zone amount decision. *Information Sciences* 280, 322–337.
- Wang, S., Sun, L., Rong, J., Yang, Z., 2014b. Transit traffic analysis zone delineating method based on thiesen polygon. *Sustainability* 6 (4), 1821–1832.
- You, J., Nedović-Budić, Z., Kim, T. J., 1998. A gis-based traffic analysis zone design: implementation and evaluation. *Transportation Planning and Technology* 21 (1-2), 69–91.
- Zhang, M., Kukadia, N., 2005. Metrics of urban form and the modifiable areal unit problem. *Transportation Research Record* 1902 (1), 71–79.