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A Review of the Redesign of Public Bus Network Routes in Iraqi Cities: A Framework Driven by Theory with a Case Study of a Mid-Size City

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Abstract: This review paper lays the theoretical foundations for redesigning public bus route networks in mid-sized Iraqi cities, with the Mid-Size City case serving as a near-future exemplification. We integrate TRNDP decision/constraint/objective structures with replicable, GTFS-based diagnostics – L-space, P-space, and route-space – to interpret transfer exposure, redundancy, and corridor coherence. Compact performance components – including expected waiting time, dwell time, commercial speed, cycle time, capacity, and accessibility – provide a concise KPI package suitable for door-to-door assessment and equity declaration. We propose that frequency-first trunks, a rational stop policy, conditional TSP, and proof-of-payment/all-door boarding constitute a practical mix for conventional buses under budget and ROW constraints. A GTFS-native pipeline produces auditable scenario packs, including a baseline, a limited-stop route, a trunk-feeder network with timed transfers, and frequency optimization under a fleet cap, along with standardized KPIs. This sets the foundation for an in-person test on Mid-Size City's Streets 40 and 60. We have decided to make Mid-Size City our proof-of-concept application domain based on two broad categories of consideration.
***Keywords*: Public transport; TRNDP; network design; accessibility; generalized travel cost; dwell time; GTFS; NSGA-II; Iraq; Mid-Size City,**

I. INTRODUCTION

Public transit buses in Iraqi mid-sized cities face an increasingly complex operating environment. With demand for urban mobility on the rise, municipal budgets and right-of-way are both limited. Iraqi cities lack standard data structures, replicable analytics, and open, auditable decision-making processes. This characterizes the extensive technical work. The intense congestion and resultant losses in travel time reliability, safety, and environmental quality caused by the increasing private vehicle ownership in cities in the Global South, including those in Iraq, are familiar. Iraq's cities exemplify a regular planning failure: much-needed contextual technical work is consistently executed without valid data structures, analytics, or finalized decision-making frameworks. In this environment, upgrading the bus networks is a mobility and policy priority, suitable for a design critique but adaptable to the institutional and data constraints of the developing world. To be more specific, the bus networks in Iraqi cities should adhere to the SSATP — Enable, Avoid, Shift, improve — standpoint, assuming a theory-first approach in the pipeline that is upfront about variables and targets. (i.e., reduce travel time
variability), or both.(T.S.P, 2020).

Throughout this work, we will use the term 'design of public transport' to refer to the deliberate, research-supported process of stating, creating, and choosing the structure and schedule of a public transit system such that it meets well-defined criteria within stated constraints. In bus networks— the transit mode on which this research focuses —design is not a unitary decision or a single static object, but a multi-level workflow. At the strategic level, it selects the topology and pattern of routes and their hierarchy, defines the roles and locations of interchanges, and determines whether the city favors direct services or a trunk-and-feeder system. At the tactical level, design sets stop spacing and location, as well as frequencies or headways by time of day, and integrates timed transfers across lines. At the interface with operations, it anticipates schedule regularity and reliability support that maintains the desired service pattern, even when vehicle bunching or running times become longer.

In each setting, the process proceeds by defining objectives and constraints, declaring decision variables, generating feasible alternatives, evaluating them using consistent metrics, and identifying the Pareto set of non-dominated solutions that simultaneously optimize user experience, agency cost, and the chosen policy criteria. This idea is related to families of problems, formalized in the literature as the Transit of Route Network Design Problem. This idea is related to families of problems, formalized in the literature as the Transit OF Route Network Design Problem. (Kepaptsoglou & Karlaftis, 2009).

“Formalize TRNDP decisions (route alignment, stop spacing, service frequencies, timed-transfer coordination). “Codify theoretical equations for generalized travel cost, dwell time, link performance, capacity, and accessibility. Propose a KPI set that incorporates equity and sustainability, in addition to conventional service metrics. “Outline multi-objective optimization approach that delivers Pareto-efficient designs given F, B. “Define GTFS-based data structures and L/P/Route-space analytics for transparent replication. Contributions. This paper unifies L-/P-/Route-space views with GTFS to diagnose and redesign bus networks, consolidates a coherent symbol set and equations for door-to-door performance, embeds equity-aware accessibility and sustainability into the objective space, and offers Scopus-ready templates for figures, tables, and KPIs for transparent reporting—paper structure. Section 2 reviews the literature and situates the conventional bus system; Section 3 surveys candidate network types (radial, grid, trunk-feeder, direct).

Section 4 develops network representations and diagnostics (L-, P-, and Route-space). Section 5 specifies the GTFS-based data model. Section 6 formalizes the TRNDP: decisions, constraints, objectives, and solution methods. Section 7 details methods and policy scenarios, while Section 8 presents theoretical equations for door-to-door performance. Section 9: stop/station policy. Section 10: includes equity, accessibility, and health/environmental co-benefits. Section 11 synthesizes the findings and identifies the research gap. Section 12 provides a summary of the section. Section 13 presents the conceptual framework. Section 14 documents the search approach. Section 15 defines KPIs and the evaluation plan. Section 16 discusses implications with reference to the Mid-Size City. Section 17 states limitations, Section 18 outlines future work, and Section 19 concludes.

II. BACKGROUND (FOCUSED ON CONVENTIONAL BUSES)

A. Rationale And Scope

The governorate of Mid-Size City is characterized by undergoing spatial growth and rising travel demand from both residents and daily commuters. The significant increase in the number of vehicles, including private ones, along with the ongoing population growth in Mid-Size City, is due to its role as a key transportation hub linking various governorates. The deficiencies and lack of integration between different transportation modes in the city, which means it is subject to a continuous increase in traffic volumes on most of its streets, which results in traffic congestion and disruption to the in general transportation system especially during peak hours; The study of area consists of two main streets in Mid-Size City City, these streets are; 40street, 60street. These streets selected for the study are among the most important arterial streets in Mid-Size City. Due to the increase in commercial, medical, and official activities, as well as the rise in demand for travel on the selected streets.

B. Public Transport — Definition, Historical Milestones, And Modal Families

Public transport – also known as mass transit/mass transport – is defined as shared, scheduled services for the general public on fixed or semi-fixed routes – creating organizational drafts that maximize the number of people moved per unit of street space and per unit of operator input. As in European cities, stagecoaches and horse-drawn omnibuses emerged in the 17th to 19th centuries, followed by a motorization climax in the 20th century, with the introduction of motor buses, streetcars, and metros. Conventional buses are the most scalable surface mode, combining low fixed costs with flexible routing.(Vuchic, 2007)

Hence, their use at all levels – including families of technologies such as bus, BRT, light rail, metro, and demand-responsive transit. Due to constraints related to the Mid-Size City’s geometry, budget envelope, and delivery timing, this review focuses ~90% on conventional buses.

1) Stage 1 — Early Urban Carriers (17th Century): The introduction of hackney coaches in London (~1600), public-hire sedan chairs in Paris (~1617; London ~1634), and Paris’s fixed-route public coach service (1662) mark the early development of urban transit.

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Figure 1 Hackney coaches(Katona & Juhasz, 2020)

2) Stage 2 — Industrial-Era Expansion (19th Century): Growing cities rely on animal-drawn vehicles; railways, tramways, and underground systems spread in late-19th-century Europe

Figure 2 Animal-drawn vehicles 19th Century(Katona & Juhasz, 2020)

3) Stage 3 — Birth of Motor Buses (1899–early 1900s): Internal-combustion buses in London (~1899) and Germany (~1903); trolleybuses emerge; motor buses become the dominant surface transport

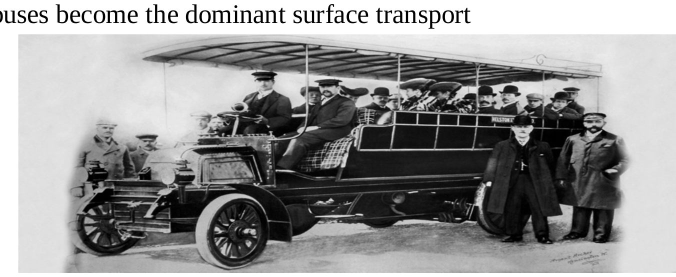
Figure 3 Motor Buses(Katona & Juhasz, 2020)

4) Stage 4 — Mid-20th Century Restructuring (1950–2000): Suburbanization, highway growth, and rising auto ownership; streetcars replaced by bus service; express/limited services grow.

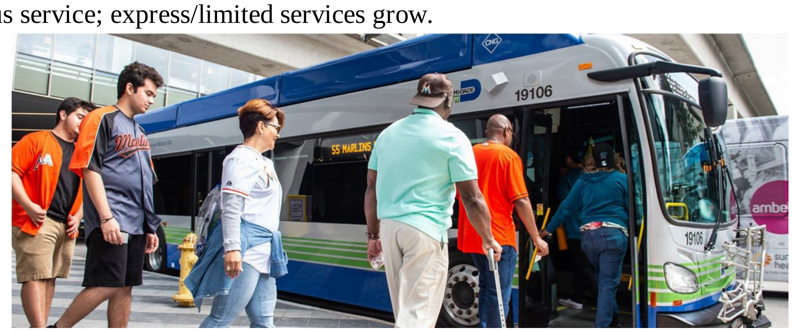

Figure 4 Bus service express(Walker, 2012)

5) Stage 5 — Contemporary Surface Transit: Conventional buses remain the most scalable surface mode (low fixed costs, flexible routing), while BRT/LRT/Metro serve higher-demand or separated ROW (Ali Fadhil Naser, 2004).

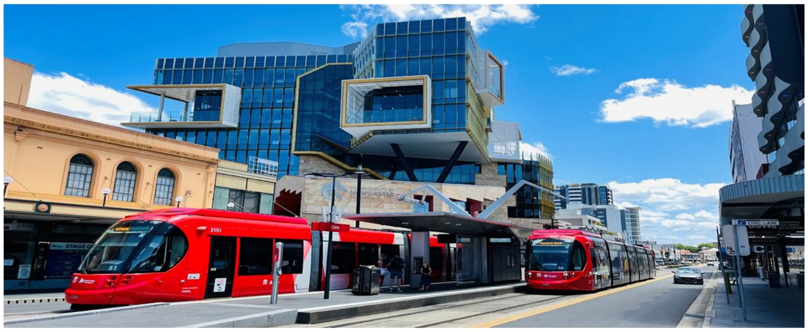

Figure 5 BRT/LRT/Metro Services(HERBERT S. LEVINSON et al., 2003)

C. *Route-Network Design — What It Means And Why Redesign Now*

Route-network design, often formalized as the Transit Route Network Design Problem (TRNDP), is a strategic and tactical process of selecting route alignments, service frequencies/headways, stop and terminal locations, and, sometimes, vehicle types, to optimize both passenger and operator goals under resource and geometric constraints. Canonical TRNDP formulations: specify objective functions such as minimizing generalized passenger travel time; agency operating/fleet costs: subject to restrictions on fleet/budget; route length/shape/directness; load factors; feasible frequency ranges; connectivity; and coverage; decision variables over which links compose each route and which frequencies/headways to run.(Kepaptsoglou & Karlaftis, 2009)

Given that TRNDP is combinatorial and multi-objective, exact optimization exhibits poor scale on realistic networks, which is why planners and researchers have heretofore resorted to constructive heuristics, local search, and metaheuristics such as genetic algorithms/NSGA-II, ant-colony methods, or particle swarm via prefixed application relatively common two-stage schemes of candidate route generation and subsequent frequency optimization: (Kepaptsoglou et al., 2010).

Multi-objective genetic algorithms (e.g., NSGA-II) provide Pareto-efficient trade-offs between passenger time and operator cost for both real demand and travel-time data. The computation is intensive. However, the outcome gives design alternatives for the planners.(Svensson, 2020.)

Redesign differs from first-time design in that it updates an existing bus network to consider new land-use patterns, area-wide demand growth, budget realities, and, occasionally, street geometry. It implies that corridor upgrading and street widenings create a time-limited opportunity to re-space stops, adjust alignments, and rationalize service routes before or suboptimal equilibria emerge—precisely the moment to act in cities undertaking vast corridor works. Data gaps, mixed traffic, tight budgets, and fragmented institutions make the simple, legible networks, disciplined stop spacing, and selective but dedicated lengthwise bus priority especially high-leverage in a developing city; moreover, passenger research confirms that reliability, comfort, and safety of stops are critical satisfaction and ridership facilitators. (Andaleeb, 2007a).

D. *Conventional Buses — Definition, Roles, And Benefits/Trade-Offs*

Conventional buses are rubber-tired, driver-operated vehicles that operate in mixed traffic or with selective priority, providing scheduled service without exclusive guideways. They deliver the quickest possible capacity increase on existing streets and can rapidly change stopping patterns and frequencies.(Vuchic, 2007).

Figure 6 Conventional bus(NACTO, 2018)

For a medium-sized developing city such as Mid-Size City, conventional buses can reliably connect neighborhoods and key government/service facilities along the City center, with direct or limited-stop patterns, minimizing transfers and access time while keeping operating costs manageable (Andaleeb, Haq, & Ahmed, 2007; Baghdad PT evaluation analogs).

Key operational requirements include fit-for-purpose stop spacing (commonly 400–600 m in built-up areas), accessible and safe stops, efficient terminals or turnbacks, and selective transit priority at bottlenecks to stabilize headways and increase commercial speed (NACTO, 2017; TRB, 2013).(nacto.org/publication/transit-street-design-guide, 2013)

Bus transportation is an urban public transport mode that uses rubber-tired vehicles operating on roadways—either in mixed traffic or on priority facilities (e.g., bus lanes, busways)—to provide scheduled, route-based services (including conventional buses, trolleybuses, and Bus Rapid Transit). (Kishore Goswami, 2024)

In developing-country contexts, buses typically form the backbone of public transport supply, complementing or substituting rail, with service performance shaped by regulatory, financial, and operational conditions. (Adinata et al., 2021)

1) Advantages And Disadvantages Of Bus Transportation

a) Advantages

Activity (incidental walking toward activity guidelines): The bus generally involves some additional walking to and from stops. A Smartcard bus-use log was matched with accelerometer data in a longitudinal study. The authors stated that bus use days were associated with 2,147 extra steps and 23 more minutes of moderate-to-vigorous physical activity compared with non-bus days. At the same time, it was found that one in four adults in the U.K. does not meet the World Health Organization's guidelines of a minimum of 150 weekly minutes of moderate activity, including walking, and that public transport–related walking accounts for 14% of this.(J. T. Evans et al., 2024)

Increased operational efficiency around boarding. All-door boarding and off-board fare payment, which are subsumed under off-vehicle fare collection in this article, shorten dwell times per passenger and increase reliability. Recent NACTO evidence suggests that dwell times can account for a significant share of bus travel time, up to one-third in certain circumstances. Moving fare payment off-board and permitting passengers to board at any door significantly reduces dwell time; in the case of San Francisco, dwell time dropped by an average of 38% after becoming the first continent-wide all-door boarding city, and average speeds increased. This, in turn, reduces transversal boardings even in the face of more freed capacity.

Network scaling and passenger experience are closely linked. Transport companies that utilize faster boarding, along with transit-priority features such as in-lane stops and rapid-transit corridors, report more even passenger loads, improved schedule reliability, and higher ridership on enhanced routes. (NACTO Policy, 2018)

b) Disadvantages / Challenges

- Note. Sedentary-time trade-off. On bus-use days, the same longitudinal study found higher sedentary time in addition to higher steps and MVPA necessitates minimizing long waiting times and the typical design of stop spacing and transfers that make access walking long and aimless(J. T. Evans et al., 2024).

- Boarding delay with cash/front-door payment. Traditional front-door, on-board cash payment takes ~ 5–9 seconds per passenger and results in queued and irregular stops; agencies using that method experienced slow and irregular dwell times.(Tanner, 2015)

E. Conventional Bus Service Typologies (Service Patterns)

Core patterns include: (i) Local (all stops), (ii) Limited-Stop/Accelerated (skips secondary stops to speed long trips), and (iii) Express (widely spaced stops with short turns as needed). Networks frequently add Trunk–Feeder structures with high-frequency trunks on primary corridors fed by shorter local routes (Kepaptsoglou & Karlaftis, 2009)

In the City center, and limited-stop trunks can move district-to-district flows quickly, while short local feeders provide first/last-mile access to dense neighborhoods and government/service.

Benefits of public bus transportation(Kishore Goswami, 2024)

1) Mobility
- Space saving
- Reduces traffic congestion
- Saves time

2) Environmental
- Reduction in per capita energy consumption

- Reduction in per capita emissions
- Reduces noise pollution

3) *Monetary*
- Saves money for individuals and households
- Improves the productivity of individuals in transit
- Increases land value in the surroundings

4) *Social*
- Improves livability in urban areas
- Encourages social interaction
- Inculcates the sharing culture
- Helps ageing & under-privileged population

5) *Safety*
- Reduced number of fatalities and injuries

F. Conventional Bus Vehicle Types (Fleet Options)

Choose vehicles based on demand and street geometry: mini/midi buses for low-demand feeders and tight turns; standard 12-m buses for trunks; and articulated units only where stop/terminal geometry and demand justify them (NACTO, 2017; Vuchic, 2007).

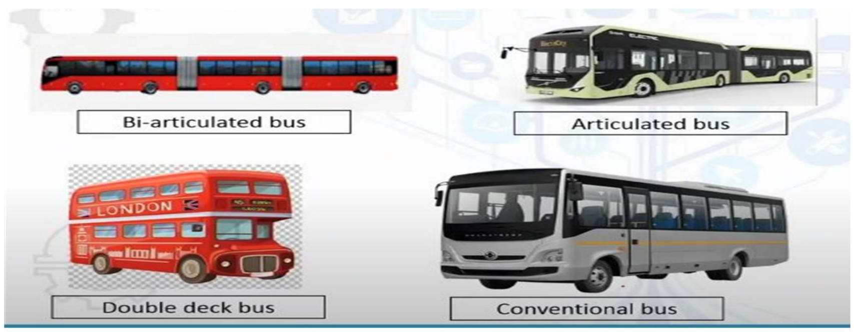

Figure 7 types of buses(Kishore Goswami, 2024)

Depending on the route or the specific network, you run only the bus types that match the demand on that route. This also provides an example of the number of passengers that can be seated and standing in every kind of bus. In Figures 7 and 8, see the various bus types. You have noticed that a conventional bus has 35-54 seats. However, in some of the buses, it was also noted that 40 passengers were seated. So potentially 19 to 40 passengers will sit in this. A standard bus can take up to 94 passengers. This must be followed as a general exercise. This is not to say that any of the buses we operate in India carry more than this or less than this, or that this is a standard we generally use, or that it is observed as the source.(Kishore Goswami, 2024)

	Seats	Standees	Total
Minibus	16-24	12-16	28-40
Conventional bus	35-54	19-40	45-94
Articulated bus	35-70	30-60	80-120
Double deck bus	50-90	15-30	65-120

Figure 8 Types of Buses: Passengers, Seats(Kishore Goswami, 2024)

G. Stops, Stop Spacing, And Terminals (Practice Notes)

The spacing of stops has a significant impact on travel time and reliability. Guidance generally recommends a spacing of approximately 400 to 600 meters in urban areas, with wider spacing suggested for limited or express services, along with adjustments tailored to specific contexts (TRB).

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Curbside and far-side stops need to have adequate length, width, and safe access. The preferred width for curbside stops is at least 2.4 meters, while the length of stops can vary between 27 and 63 meters, depending on the length of the bus and operational requirements. (NACTO, 2013.).(nacto.org/publication/transit-street-design-guide, 2013)(Moran et al., 2013)

- Operational efficiency of boarding is maximized. All-door boarding and off-board fare (proof of payment), as well as allowance for passenger dwell times and reliability. According to the supportive evidence of NACTO, dwell can account for up to one-third of bus travel time on average. By moving payment off-board and opening all doors to boarding, it dramatically reduces dwell time to a baseline percentage (e.g., a no-cost 38% average reduction in the city of San Francisco after all-door boarding system-wide implementation). Additionally, it improves speeds, albeit with higher boarding rates.
- Network scalability and rider experience. Faster boarding offers a more substantial transit-priority design. For instance, most agencies have in-lane stops and signal priority for train-street rapid transit, reporting steady passenger distribution, schedule adherence, and ridership growth on numerous improved lines. (NACTO, 2017; NACTO, 2018).
- Sedentary-time trade-off. On bus-use days, the same longitudinal study observed higher sedentary time alongside higher steps and MVPA—suggesting a need to minimize long waiting times, and design stop spacing and transfers that keep access walking short and purposeful.(J. T. Evans et al., 2024)
- Boarding delay with cash/front-door payment. Traditional front-door, on-board cash payment adds ~ 5–9 seconds per passenger, creating queues and unreliability at busy stops. Agencies relying on this practice experience slower and more variable dwell times. NACTO. Bus Operator Guidelines: Addis and Seville. 2017. Due to concurrent operation and looming policy entanglement (NACTO, 2017).

In this paper, we translate that scaffold into a theory-first, GTFS-native pipeline: 4 estimating Access and transfer penalties; and optimizing route layouts, frequencies, and stop spacing under fleet and budget constraints. By design, this orientation targets the specific needs of mid-sized cities, where incremental speed and reliability gains can materially reduce generalized travel costs, while remaining auditable and replicable in data-scarce environments.

Policy Tool: Stop Spacing Guidelines

	Previous Policy	New Guidelines
Bus	~ 800' to 1,000' (grade ≤ 10%) 500' to 600 '(grade 10%-15%) Bus stops may be spaced as close as 300' to 400'(grade > 15%)	~ 800' to 1,360' (grade ≤ 10%) Bus stops may be as close as 500' (grade > 10%) Limited and Express stops to be spaced on a case-by-case basis

Figure 9 Stop Spacing Guidelines(Tanner, 2015)

H. Developing-City Specifics

Developing-city operations face mixed traffic, constrained funding, fragmented governance, and data limitations; passenger research highlights reliability, comfort, and safety at stops as key drivers of satisfaction and ridership. (Andaleeb, 2007b)

In contrast, at City Center/60, selective priority treatments—such as queue jumps, transit signal priority, and targeted bus lanes—can yield substantial travel time savings from delay-prone sections. However, public transport planning in developing regions must contend with rapid urbanization, constrained institutions, and data scarcity, as the SSATP background clarifies: “The lack of reliable and comparable data is a big issue for those working on urban transport” in mid-sized cities, where most residents reside. The mobility burden is severe. In some African metros, “it can take anywhere from two to four hours in any direction to reach workplaces and other economic opportunities”. These congestion pressures are further exacerbated by the rise of informal settlements and the collapse of formal services. “Rapid and unplanned growth… is accompanied by the decline of formal transport systems and the emergence of informal options.” Dependence on resources varies. Some large cities, for example, “have no planned public transport and no public organization dedicated to managing the system,” leading to perennial congestion and low prioritization of mobility inefficiencies. In mid-sized cities, such as those in Iraq, these accessibility deficits are also evident, albeit with less urgency and coordination. Infrastructural investments, ranging in scale, also characterize interventions feasible for the mid-sized context—such as Iraqi secondary cities. The SSATP’s EASI approach, which consists of four levers — Enable, Avoid, Shift, and Improve — provides a high-level organization around which bus network design and service planning can be structured. Baghdad exemplifies a rapidly growing, developing city context.

The bus system of GCPT cores the public transportation in a mixed-traffic context with challenging demand-supply dynamics—stations that are crowded, illegally parked, complex terminal dwellings, and mixed traffic. Such a context is generic to mid-sized cities in the Global South. Thus, a standardized Level of Transit Service framework is essential before reforms. The reference study employs a reusable framework that measures a consistent set of operational indicators—travel time, headway, hours of service, total delay, adjusted running speed, in-vehicle density, and capacity—to diagnose service quality and then design a tailored package of operational/traffic interventions. (Ali Fadhil Naser, 2004)

In this paper, we have translated that policy scaffolding into a theory-first, GTFS-native pipeline: diagnosing existing bus networks with L-/P-/Route-space metrics, encoding realistic service patterns, optimizing route layouts, frequencies, and stop spacing under fleet and budget constraints. This enables an orientation that is adapted to the particular demands of mid-sized cities–to reduce generalized travel costs meaningfully, marginal speed and reliability enhancements are sufficient. At the same time, it remains auditable and replicable in data-limited environments.

DRT: flexible coverage at low density; low corridor throughput—best as feeder/coverage (NACTO, 2017; TRB, 2013).

III. CANDIDATE NETWORK TYPES (RADIAL, GRID, TRUNK–FEEDER, DIRECT).

Scope and intent. This section specifically (a) refers to the conventional city bus networks, not BRT; (b) defines four canonical network types; (c) explains when and how one is used over the others; and (d) summarizes which tends to be better for economics and (perceived) speed, according to the literature. While this study does not aim to provide a theoretical typology of network forms – radial, grid, trunk-feeder, direct – but merely documents network composition in a particular, pragmatic way – more than seven routes as major, whereas others as minor – and an inventory of the routes and their operating characteristics, thus being useful for contextual priming to recommend future research agendas concerning formal network typologies in the literature.(Ali Fadhil Naser, 2004).

A. Definitions And Use-Cases (Conventional Bus)

1) Radial / Hub–Spoke.

Definition: Core are the lines that all converge to a dominant core and radiate outward. The Hub-Spoke is a variant of the Lines that consolidates flows at one or more Hubs connected by high-capacity inter-hub links and fed by short feeders, which connect neighborhoods to the hubs. Viable use cases: Most appropriate when most trips robustly pour into a single CBD and dispersion is low to moderate.

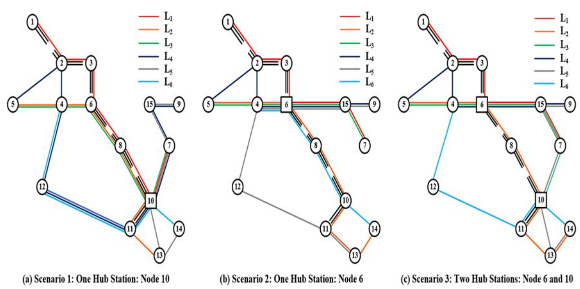

Figure 10 Bus network scenarios under alternative hub-station configurations: (a) one hub at node 10; (b) one hub at node 6; (c) two hubs at nodes 6 and 10. Lines L1–L6 shown. Walker (2012, Human Transit).

Transfers are rare, and legibility is high—economics & speed.

- Planners reiterated that the beneficent reorganization of flows onto hubs yields economies of scale on critical inter-Hub links, which allows regular headways and decreases fleet. However, individual path times may rise slightly, which is a trade-off that favors the system.
- Prior recommendations for line reconfigurations are more detailed in earlier guidance on route reconfiguration. A fact-based assessment of radial reconfigurations ranked as neutral, with attention to context. (J. E. . Evans et al., 2003)

Practical design/redesign notes.

- Hubs should be picked and sized where multiple high-demand corridors meet. Feeder routes should be short and direct. Segments of a mile and a half, or often more, are not ideal; an aperture such as this can be walked safely and rapidly. Pratt (2004), TCRP Report 95; (Hosapujari & Verma, 2013) Procedia–Social and Behavioral Sciences.

Figure 10a schematically represents a typical hub-and-spoke network that was originally predictable. All nodes are not directly connected, but are allocated just one hub node at any non-hub node; thus, this is referred to as the single allocation p-HLP. Additionally, many restrictions are further relaxed in some studies to improve adaptability to various conditions. By utilizing the multiple allocation policy, Campbell extended the p-HLP in 1996. Since each of the non-hub nodes can be allocated to more than one hub node, the model is recognized as the numerous allocation p-HLP. Moreover, the restraint on hub utility assigned in Aykin 1995, entitled nonstop service (refer to Figure 10b), implies that the spoke nodes in the spoke can be interconnected to Noma hubs by consuming any hub. (Huang et al., 2018)

2) Grid

Definition. That is, orthogonal lines (N–S / E–W) at planned spacing such that most residents are within a short walk of two lines: most trips are completed with one right-angle transfer (an ‘L’ path)

Use cases. Grids work best in multicentered, dispersed cities when the operator affords high all-day frequencies and spans to keep transfer penalties low—evidence from economics & speed.

- The researcher also noted that frequency and span are the essence of freedom from the user’s viewpoint; grids deliver near-anywhere-to-anywhere access with a single transfer only if high frequency is sustained.(Walker, 2012)
- Later synthesis work found that agencies with frequent networks to gain massive accessibility increases (jobs in X minutes) and user reliability when frequency was made more possible. (Byala et al., 2019)

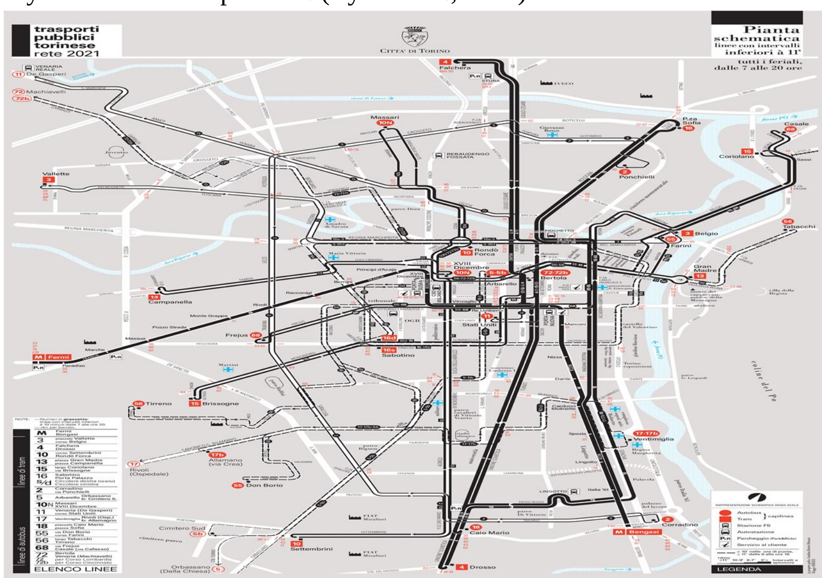

Figure 11 Grid-dominant hybrid with Trunk–Feeder elements **(** Byala et al., 2019)

Practical design/redesign takeaways

- Corridor spacing should be determined to match a target maximum walk ... and headways should be consistent across intersecting lines wherever feasible to simplify pulsed connections and minimize the perceived transfer penalty. Source: Human Transit; Byala et al. 2019...... TCRP Synthesis by Walker from 2012

3) Trunk–Feeder (Transfer-Oriented)

Definition. High-frequency trunks operate on the most productive corridors; short feeders transport passengers to and from trunk stops or hubs; and transfers are a deliberate element of design—use cases. Suitable in case of the concentration of passenger flows on several axes, but the population of neighborhoods is relatively low; the key to success is minimizing the transfer penalty δ *—economics & speed evidence.

- Transfer-based designs become more and more competitive with the increase of urban dispersion; the only” size” of δ determines how much more competitive they are compared to the counter concept – direct patterns. The Spanish case study demonstrated that hub–spoke/trunk systems incur a lower penalty when increasing δ. — Badia et al. 2014, Transportation Research Part A; Badia et al., 2019, European Transport Research Review.

- Practical application found that reducing the total number of buses by ≈13.6% and, simultaneously, increasing overall passenger time by ≈2.1%, is an acceptable cost efficiency for regular buses. – Hosapujari & Verma (2013). Practical design/redesign notes.
- Focus on the most productive corridors for frequent trunks, make feeders legible, and optimize transfers based on changes that could reduce δ. – Badia et al. 2014, 2019; Hosapujari & Verma, 2013.

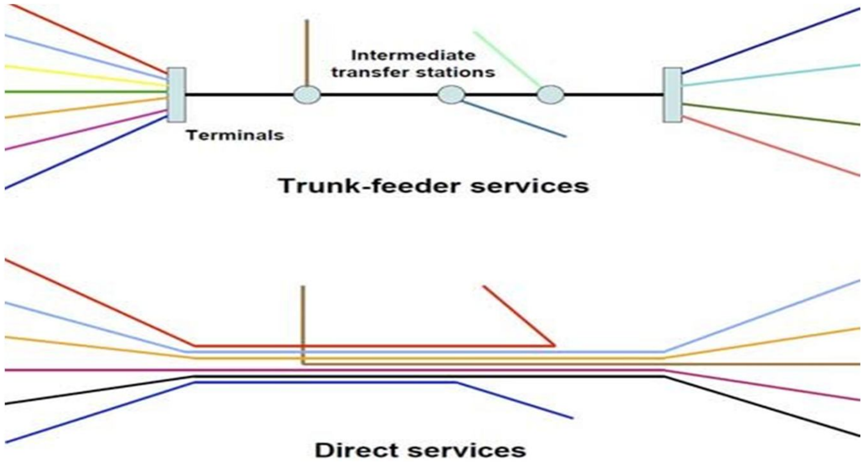

Figure 12 Trunk–feeder services (top) versus direct services (bottom): feeders connect to a high-frequency trunk with intermediate transfer stations, while direct services run end-to-end without transfers. (Prayogi, 2015)

4) Direct (Point-to-Point / Direct-Trip-Based)

Definition. Provision of direct lines for specific origins and destinations, avoiding the need for transfers; often applied when substantial amounts of stable, strong OD demand regularly occur between a small number of centers. b. Use cases. Handy in the case of intermediate dispersion with several major OD pairs; as direct lines spread across the network, the level of overlap and the headways spread diverge, negatively affecting the Christopher streetcar and trolley system. c. Economics and speed. Evidence

- As already mentioned, it has been claimed that direct systems are fragile in the face of headway constraints, which may be relatively limited by the number of lines and issues with stops; the more of them there are, the less reliable and high-speed it feels. —(Badia, 2020) European Transport Research Review. Hosapujari & Verma note that in earlier practical accounts, extensive point-to-point patterns are seen as "patterns consisting of large numbers of mostly overlapping lines that are hard for both passengers to understand and for operators to operate.

Practical design/redesign notes.

- In a later edition, Badia et al. maintain that "use direct lines sparingly for the strongest markets (e.g., university – CBD) and protect headway regularity on the rest of the system; otherwise, the cost of complexity outweighs the benefit of zero-transfer for the few".

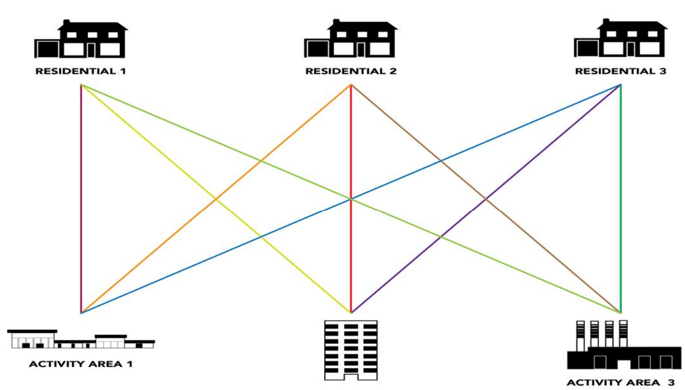

Figure 13 Connective Option (Walker2012)

B. Bus Operation In Central Business District (CBD)

Planning CBD bus routes. When planning CBD bus routes, the divide between streets should be taken into account, along with entry points, employment centers, terrain, and service provisions. The fact that "Routes focusing on a small number of CBD 'spine' streets instead of a dispersed grid will clarify the service and schedule and will put enough buses there to allow priority treatments to work," on a minimum cost basis, is in fact foundational. Ali Fadhil Naser said, "In downtown areas, the CBD treatment lengths consist of bus streets and bus-only lanes. Even though they are cost-effective low-capacity systems, bus streets and bus-only lanes are the most frequently used modes in areas of high-density and are the most effective measures in the city's view." CBD CBD CBD-alignment and spacings should correspond with the street align grid, key access points, terrain, several of the most significant clusters of employment, and service frequency (Washington, 1980; Al-Maaini, 2002).

Ali Fadhil Naser noted with much concern that: "Urban streets in which buses are operated in mixed traffic need only to be dedicated with a policy, and little more can be done, although almost any routing is feasible. However, establishing a high level of control requires that autos and other traffic generate little durable retardation; otherwise, only departures surge legs of commercial speed will be within the range of the private transportation car. Priority treatments are autonomous and almost impossible to achieve in mixed traffic CBD. They should increase speed, reliability, reduce random delay opportunity, increase person-throughput, and encourage travelers into high-occupancy patterns, particularly near intersections" (Ress & James, 1982). "Arterial streets are the minimum cost method for enhancing road utilization efficiency or increasing bus service and prestige—permitting buses to overtake each other reaching the station". CBD "CBD bus routes, are run along, appropriate levels of street-grid alignment, of service frequency, and over a route that minimizes turns, and of likely levels of stop use, frequency". CBD.

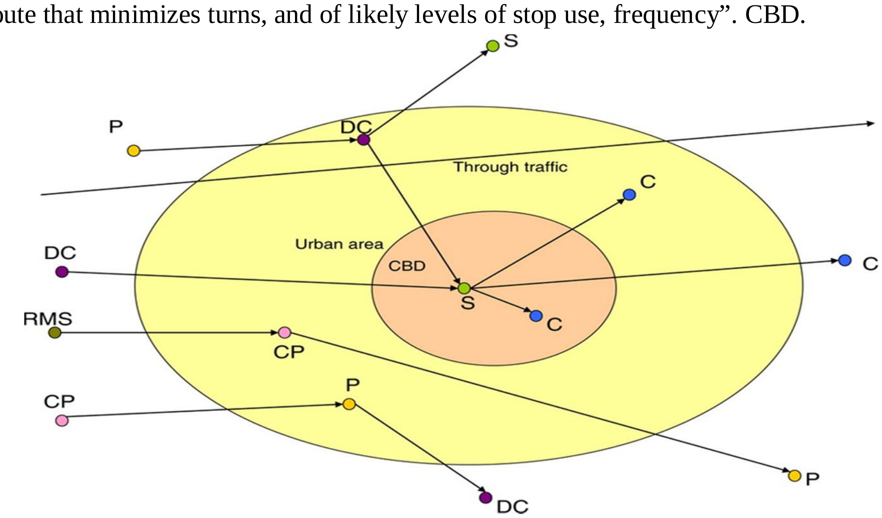

Figure 14 Direct services with through-routing across the CBD: long point-to-point lines connecting peripheral origins/destinations without transfers.(Behrends et al., 2008)

C. Types of CBD Street Treatments:

1) Bus Streets

Al-Maaini (2002) stated that bus streets might include four typical concepts:

- Terminal approach: Exclusive access to a downtown bus terminal and connections to express highways or busways.
- Bus loop: a series of streets designated exclusively for buses, forming a loop
- Short connector Links are short segments of dedicated bus-only roadways providing direct service where street continuity is poor, and bus travel along arterial streets is indirect and slow.
- Bus-pedestrian mall: Downtown bus routes and streets providing direct bus access to central generators.

2) Bus Lanes

The HCM 2000 and Jacques and Levinson 1997. A bus lane is defined as any lane on a roadway where buses operate. It can be exclusively designated for buses or shared with other vehicles. Buchanan and Coombe 1973 defined the business in which:" If bus lanes are designed to reduce non-bus traffic capacity, this measure not only benefits the bus at the measure but also, by modulating the amount of traffic able to pass, but prevents another queue from forming on them; thus further benefits buses." Hobbs 1979 classified bus lanes by separation into three types:

3) Bus lanes with–flow lanes (Regular lanes):

Usually, curb lanes are used by buses only, marked by pavement markings, signs, and sometimes rubber cones (although no fixed physical barriers are used).

4) Contra-flow Lanes

Regular traffic lanes reserved for buses but operated in the opposite direction to all other lanes (often used to avoid lengthy detours in one-way systems; controlled by overhead lane signals).

5) Exclusive bus-only lanes

Physically separated from other lanes by curbs, fences, greenery, or grass dividers; these include curbed medians, bus malls (streets limited to pedestrians and buses, usually in CBD), and grade-separated roadways for high-speed, interference-free bus operation.

Moreover, HCM (2000) classified exclusive bus lanes according to the use of the adjacent lane by other traffic:

Type (1): bus lane without an adjacent lane.

Type (2): bus lane with partial use of an adjacent lane.

Type (3): bus lane with two lanes for the exclusive use of buses.

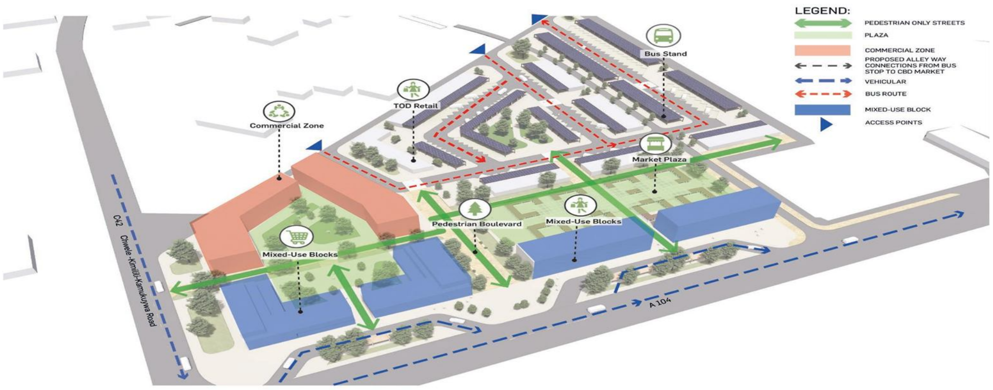

Figure 15 Diagram explaining Circulation and Access to the Bus Park Site (https://issuu.com/about)

D. Bus Preferential Treatments At Intersections

According to Vuchic, “most traffic delays are caused by intersections; hence, speeding up the bus travel through intersections is particularly crucial”. For this reason, streets with transit service are generally favored. Besides, the scholar mentions that at an unsignalized intersection, “the cross streets are to be stop or yield signed to facilitate vehicle movements”. The bus preferential treatment at intersections is described in HCM:

1) Signal Priority: includes passive systems; pre-timed/offset settings adjusted manually to balance transit benefit with minimal impacts; active integrated systems signal timing adjusted after detecting a bus. Bypass: enables buses to avoid queues, e.g., at signalized intersections or ramp meters closed, by providing a special lane. Queue-bypass lanes can be shared with personal vehicles.

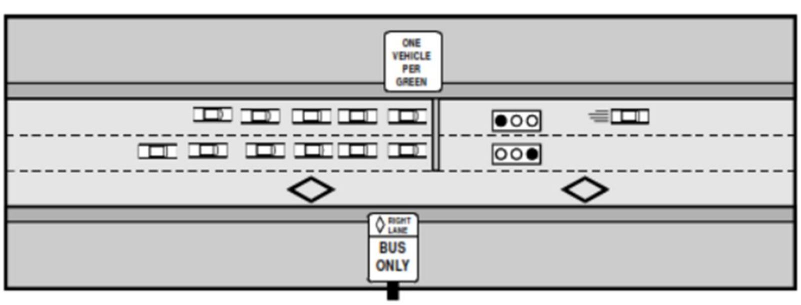

Figure 16 Cars queue at the ramp meter(Part 2/BUS TRANSIT CAPACITY 2012.)

2) Queue Jump: Buses may pass long queue lines backing up at signals using right-turn lanes or long off-line bus stops; buses may receive an early green to merge ahead of general traffic.

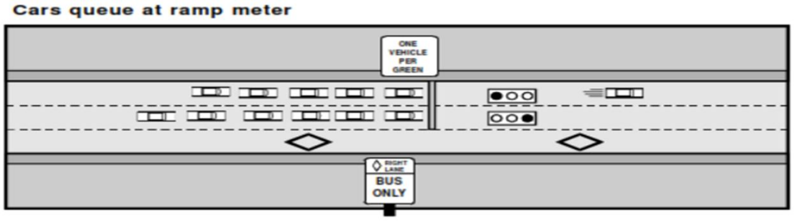

Figure 17 The bypass lane allows the bus to avoid the queue.

3) Curb extensions: Extend the curb into the parking lane so buses stop in the travel lane to board/alight without needing to merge back headway; especially useful where there is curbside parking and high traffic volume.
4) Boarding island: enables buses to stop between travel lanes and remain in a faster lane; pedestrian safety must be addressed.

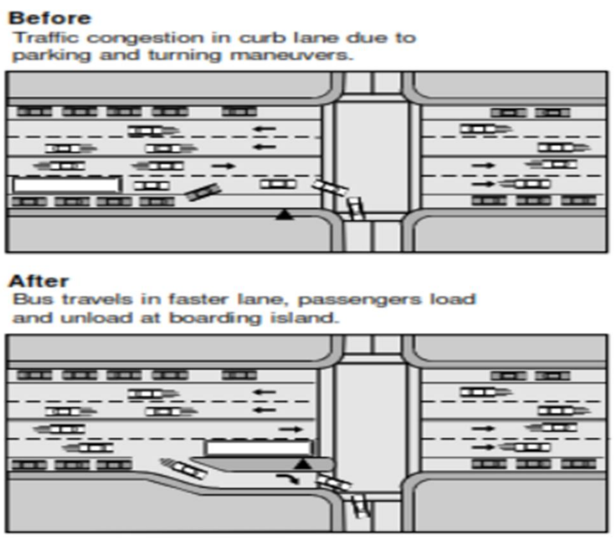

Figure 18 Boarding Island Concept (TCRP, 2012)

5) Parking restrictions: On streets where high parking turnover interferes with traffic signal progression, parking restrictions are used to improve transit and traffic flow; bus operations are often restricted to peak hours.
6) Bus stop relocation: On streets with good signal progression, moving a stop from near-side to far-side may let buses use green waves—dwelling on red and passing on green.

Turn-restriction exemptions occur when turn bans block direct bus routing. A left-turn prohibition might be imposed for capacity reasons, but selective exemptions may be feasible if safety is not compromised. (Pandu, 2000; Al-Maaini, 2002).

IV. NETWORK REPRESENTATIONS (L-/P-/ROUTE-SPACE) AND DIAGNOSTICS

This subsection defines the major graph representations of Public Transport Networks (PTNs) used for PTNs, describes what each is ideal for, and also maps them to real city cases, explaining what a mid-sized city like Mid-Size City requires. Over the past few years, researchers have conducted studies on the topology and relevant characteristics of public transport networks. The researchers' focus was on analyzing, planning, regulating, and optimizing their behavior, cost, and efficiency, among others. In particular, complex network theory is applied to massive and complex systems, such as PTNs, to analyze and understand their properties.

Sienkiewicz and Hołyst formalize two canonical PTN views. I. L -space: stops are nodes; an edge exists when two stops are served consecutively by a route. Thus, the shortest paths count stop-to-stop hops. II. P -space: stops are nodes; an edge exists if two stops are on at least one standard route, and they are thus reachable without transfer. They report small-world behavior and distinct degree distributions across spaces – power-law-like in L; exponential-like in P.

Use: L-space is ideal for corridor diagnostics (stop spacing, local connectivity, and transfer exposure along lines). P-space is perfect for studying transfer requirements and one-seat ride reachability. Global examples: Their analysis encompasses multiple Polish cities of varying sizes, illustrating space-dependent diagnostics.(Sienkiewicz & Hołyst, 2005)When dealing with spatial.

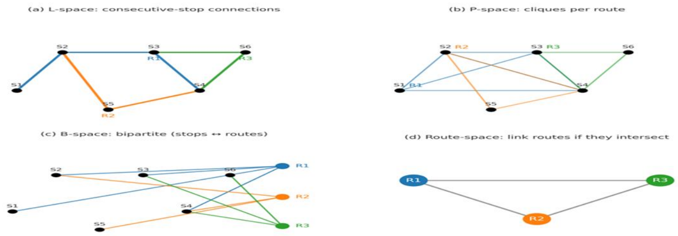

Figure 19 PTNs Conceptual (Sienkiewicz & Hołyst, 2005)

A. *Extending TO B-/ROUTE-Space*

Von Ferber et al. (2008) extended the toolkit to include a bipartite B-space and its projection, Route-space (also often referred to as C-space), where routes are nodes connected if at least one stop is shared—for example, PTN across fourteen world cities and how the metrics change with the chosen representation. Use: Route-space is strong when the analysis is on the line level – overlaps, interlining, and where operational risks accrue (e.g., highly overlapping routes/fadeable interchange lines). Global examples include European and select large global metro and bus systems from their sample, which can be compared across cities.(von Ferber et al., 2008)

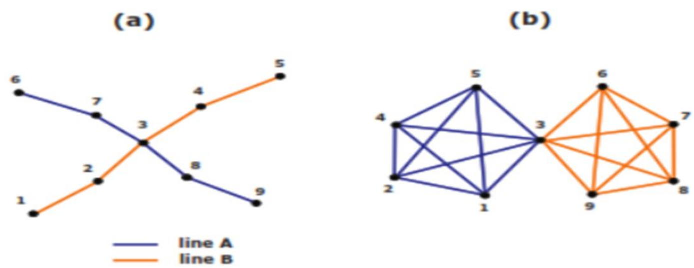

Figure 20 Network representations: (a) L-space (adjacency of consecutive stops on each line); (b) P-space (complete subgraphs for stops belonging to the same line). Lines A and B are shown.(von Ferber et al., 2008)

B. *Reproducible Network Building And Metric Computation (OSMNX)*

Boeing (2017) presents OSMnx, which simplifies the reproducible assembling of graphs and the calculation of metrics from OpenStreetMap. While it has been proven on street networks, the same method can be adapted to PTN preprocessing, including spatial cleaning, watermarking, and exporting graphs for L-space inspection and map-matched diagnostics.

Application: Develop a regular PTN graph or street levels for approaching bus stops, calculate centralities, and path lengths. Examples can be found all over the globe, such as urban studies (PDX) or extensive, multi-urban data accumulation processes that are scalable. (Boeing, 2017)

V. WHAT GTFS IS AND WHY IT MATTERS

General Transit Feed Specification, or GTFS, is a machine-readable format that describes protected transit schedules, stops, routes, trips, and service calendars. A GTFS-rt feed includes live trip updates, vehicle positions, and service alerts. A multi-system pilot's direction is consistent with feeds, centralized repositories, and standard creation workflows that feed maintenance cycles, improve data quality, and enable the ability to find feeds, empowering them to bring broader distribution to first- and third-party apps.(Sophie Abo et al., 2024)

A. *Static Versus Realtime: Roles And Trade-Offs*

GTFS-Static captures planned service and is indispensable for baseline coverage, headway, and accessibility analysis. However, schedule-based accessibility can be biased relative to experienced travel times—often by 5 to 15% in high-access areas—due to delays, non-adherence, or detours. (Wessel & Farber, 2019)

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VI. TRNDP/TRND: DECISIONS, CONSTRAINTS, OBJECTIVES, AND SOLUTION METHODS

This section provides the context for addressing the Transit Route Network Design Problem (TRNDP) by exploring the real-world constraints of fleet, budget, geometry, and service standards, within which the four major decisions—route alignments, frequencies, and stop/terminal placement—are made. Additionally, we define our objectives as being balanced between passenger-centered and operator-centered actions. Finally, we provide an overview of primary methods used to discover responses, from analytical and mathematical programming to heuristic and metaheuristic methods in use today.

VII. BUS STOP PLACEMENT

The distance between stops has a significant impact on travel times. More closely spaced stops provide customers with shorter walk times, but they also increase travel times, which is a significant reason transit is slower than automobile travel. Each additional stop requires the bus to decelerate, come to a complete stop, load and unload passengers, and then accelerate and re-enter traffic. Most customers want transit services that strike a balance between convenience and speed, and the number and location of stops are key components in determining that balance.(BCDCOG, 2021)

A. Key Takeaways

- When possible, make bus stops accessible by a sidewalk in good condition, between the bus stop and the nearest intersection.
- Bus stop placement should be responsive to central activity generators and should have a direct, accessible path to them.
- When possible, place bus stops on the far side of intersections.

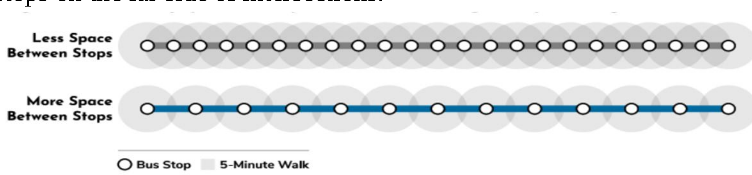

Figure 21 Too Closely Spaced Bus Stops Slow Service without Significantly Increasing Access to Transit

B. Stop Pairing

Whenever possible, bus stop locations should be paired so that customers board and alight on opposite sides of the same street in the same vicinity when making a round trip. This enables the transit service to be more intuitive and maximizes convenience for the largest number of users. (BCDCOG, 2021)

C. Stops with High Transfer Activity

At locations where transfer activity between routes is heavy, bus stops for the intersecting routes should be located as close to each other as possible to shorten the travel time for passengers transferring between routes. (BCDCOG, 2021)

LONGITUDINAL POSITION (NEAR-SIDE / FAR-SIDE / MID-BLOCK): NARRATIVE COMPARISON(Transit And Bus Stop Design Guidelines, 2021)

- Near-side: Stop before the intersection (approach side).
- Far-side: Stop after the intersection (departure side).
- Mid-block: Stop between intersections (away from corners).

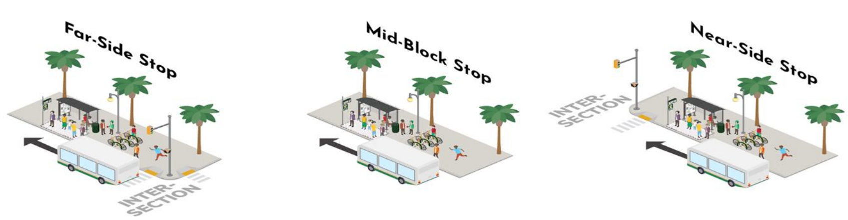

Figure 22 NEAR-SIDE / FAR-SIDE / MID-BLOCK (BCDCOG, 2021)

D. Near-Side (Before The Intersection)

Key advantages — Omnitrans explains that placing the stop on the approach side keeps the door close to the crosswalk, allows the operator to see oncoming buses for transfers, and enables the bus to use the intersection gap to merge. At unsignalized approaches, it can also coincide with the mandatory stop, reducing double stopping.

Potential drawbacks — Near-side stops can conflict with right-turning traffic, obscure sight distance for drivers and pedestrians, and, at signalized junctions, add delay if queues form ahead of the stop.

Use when… — Downstream spillback would block a far-side stop, the landing area or pedestrian desire lines are better on the approach side, or local constraints (curb/driveways/sight distance) favor the near-side. — Omnitrans Transit Design Guidelines (2023), Appendix D.

E. Far-Side (After The Intersection)

Key advantages — Omnitrans and BCDCOG/CARTA note that far-side siting avoids right-turn conflicts, facilitates smoother re-entry after the signal (natural gaps), and pairs well with Transit Signal Priority (TSP); it is generally preferred at complex, multi-phase signals. (BUS STOP, 2021)

Potential drawbacks — If the stopping area is too short, queued buses may spill back into the intersection; the far side also requires adequate landing space beyond the crosswalk.

Use when… — Intersections are signalized (especially with TSP), turning movements are heavy, or the far side offers better boarding pads and pedestrian conditions. — Omnitrans Transit Design Guidelines (2023).

F. Mid-block (Away from the Intersection)

Key advantages — Mid-block siting can place the door directly in front of central generators that are not located at corners, thereby reducing interaction with turning movements.

Potential drawbacks — Most guides discourage mid-block because it can encourage mid-block crossings (safety/legibility issues), add jaywalking risk, and lengthen access to protected crossings.

Use when… — Large attractors sit mid-block, and safe intersection siting is infeasible; provide protected crossings and continuous sidewalks if a mid-block stop is unavoidable. — Omnitrans Transit Design Guidelines (2023), Appendix D.

Table 1 Recommended and Maximum Stop Spacing for Local Fixed Routes — adapted from BCDCOG/CARTA (2021).

Bus Stop Spacing Standard	Local Fixed Routes
Recommended Stops per Mile	4–6
Recommended Spacing between Stops	1,300 feet
Maximum Stops per Mile	8
Minimum Spacing between Stops	660 feet

VIII. EQUITY, ACCESSIBILITY, HEALTH, AND ENVIRONMENTAL CO-BENEFITS

Equity and accessibility are central to public transportation planning, ensuring that safe and reliable services reach low-income neighborhoods, women, older adults, and people with disabilities—closing spatial and social gaps in opportunity. At the same time, shifting trips to efficient bus networks delivers health and environmental co-benefits by reducing air pollution, traffic injuries, and greenhouse gas emissions, while promoting more active and walkable streets.

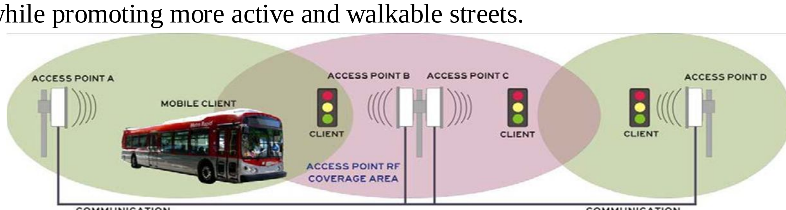

Figure 24 ACCESSIBILITY: FROM MOBILITY TO ACCESSIBILITY (Wessel & Farber, 2019)

Contemporary equity practice treats accessibility as a distributional objective. A behaviorally grounded measure is the logsum from discrete choice models, which captures changes in generalized travel cost and destination utility and enables distributional analysis. — Using the Logsum to Explore Transport Equity in Public Transport(Zhu et al., 2017)

IX. SYNTHESIS AND RESEARCH GAP

A. Synthesis

The literature converges on a few robust ideas for conventional city buses. First, network form follows demand geography: radial/hub–spoke performs best where a single CBD dominates; grid enables anywhere-to-anywhere access when high all-day frequency is affordable; trunk–feeder (with timed transfers) gains advantage as dispersion rises, provided the transfer penalty (walking, waiting, wayfinding) is actively suppressed; and selective direct lines may complement trunks for a few strong OD pairs but quickly erode reliability if they proliferate. Across forms, economics hinge on commercial speed, dwell control, and concentrating frequency where returns are highest. Second, the TRNDP/TRND strand shows that agency objectives (fleet, VKT, operating cost) and user objectives (waiting, in-vehicle time, transfers) can be balanced via single- or multi-objective models. Modern metaheuristics (GA/NSGA-II, ALNS, VNS, PSO, etc.) are routinely employed to search large design spaces. At the same time, schedule-aware evaluations (headways, timed transfers, and capacity feasibility) are crucial for achieving realistic outcomes.

Third, theoretical performance components are well-specified and reusable: expected waiting. $\mathbb{E}[\text{Wait}] \approx H/2$; dwell driven by a fixed door time plus boarding/alighting service rates; link capacity as frequency × vehicle capacity × usable load factor; and cycle time propagation for fleet sizing. These expressions connect design choices (such as stop spacing, all-door boarding, and TSP) to both user and operator costs. Fourth, bus stops and stations matter as much as lines: placement (far-side at signals), curbside vs. layby trade-offs, context-based spacing (tight in dense activity centers; wider on faster segments), ADA-compliant pads and CPTED lighting, and operational enablers such as Proof-of-Payment and Transit Signal Priority (preferably conditional). These levers directly affect dwell, reliability, and perceived speed. Finally, equity-oriented planning reframes success from mobility to **accessibility**. **Logsum-based** accessibility and **TOD** (station-area walkability, mixed uses, safe crossings) provide a consistent way to measure distributional gains, especially for car-less and vulnerable groups.

B. Research Gap

1) Integrated policy bundle for conventional buses. Much work treats elements in isolation (e.g., spacing or TSP). However, fewer studies co-optimize: (i) stop spacing and stop form (curbside/layby), (ii) timed transfers on two orthogonal trunks, and (iii) frequency allocation under a hard fleet cap, with all pieces evaluated together through dwell/transfer penalties and capacity feasibility.
2) Context-specific calibration. Typical values for boarding rates, transfer penalties, and pedestrian access are often borrowed from other regions. There is a need to calibrate these to a Middle Eastern, medium-speed arterial context (e.g., Mid-Size City's 40/60 corridors) and to test their sensitivity.
3) Equity-ready TRNDP. Methods frequently optimize total or average performance; fewer embed minimum accessibility constraints for priority zones while still meeting fleet and reliability constraints.
4) TOD–bus interface at trunk hubs. Evidence shows that TOD improves access, but practical guidance is lacking on pulse design and street cross-section choices (such as curbside/layby, queue-jumps, and signal priority) within TOD catchments for conventional buses (not BRT).
5) Reproducible GTFS/OSM workflow for redesign. A standardized, graph-based (L/P/Route-space) pipeline that the agency can reuse—linking scenario GTFS to optimization and equity/accessibility reporting—remains under-documented for cities with limited data.

This thesis addresses these gaps by (i) formulating a theory-first objective/constraint set grounded in the dwell–waiting–capacity equations, (ii) packaging a GTFS/OSM pipeline that builds L/P/Route-space graphs, (iii) testing four scenarios (baseline; limited-stop priority; trunk–feeder with pulses; frequency optimization under a fleet cap), (iv) embedding equity constraints on minimum accessibility, and (v) applying all of the above to Mid-Size City's Streets 40 and 60 with context-sensitive stop spacing and stop form (curbside vs. selective layby) plus conditional TSP.

X. SECTION SUMMARY

This chapter reviewed the strands needed for a practical redesign of a conventional bus network:

1) Background → Definitions → History → Benefits → Modes → Bus Pros/Cons → Developing-City Context: Establish core terms (route, headway, transfer, accessibility) and a brief arc from early tram/bus systems to today's multimodal networks; synthesize the benefits of public transport (congestion, equity, emissions, safety, affordability); position modes by typical capabilities (capacity, speed/ROW, reliability, cost) with emphasis on bus/BRT; distill buses' advantages (flexibility, low capex, rapid deployment) and limitations (mixed-traffic delay, variable reliability, fleet/ops needs); and frame design choices for developing, mid-sized cities under budget/street constraints—prioritizing scalable, frequent, coverage-conscious bus solutions that can evolve toward BRT where demand warrants.

2) Network forms (Radial, Grid, Trunk–Feeder, Direct). When and why each works; the central role of frequency and transfer quality; and the risks associated with excessive direct lines for reliability.
3) TRNDP/TRND foundations. Single- and multi-objective formulations balancing user and agency costs; modern metaheuristics to search large design spaces; and the importance of schedule-aware feasibility (fleet cap, load factors, timed transfers).
4) Performance components. Compact expressions for waiting, dwell, capacity, run/cycle time, and fleet that turn design choices (spacing, boarding method, TSP) into measurable user and operator impacts.
5) Stops and stations. Policy guidance on far-side siting at signals, curbside vs. layby selection by context, stop spacing bands that balance access vs. speed, and the operational value of PoP, near-level boarding, and conditional TSP.
6) Equity, accessibility, and TOD. Moving from mobility to accessibility (logsum) and using TOD to raise walk access share, reduce last-mile penalties, and support distributional goals for vulnerable groups.
7) Mid-Size City linkage. Streets 40 (N–S) and 60 (E–W) are designated as frequent trunks. Policy bundles—located far-side at signals, curbside by default with selective layby at high-dwell sites, context-based spacing, PoP, and conditional TSP—form the practical design palette to be tested in the application.

These findings set up the Methods chapter: we will implement a GTFS/OSM workflow, construct L/P/Route-space graphs, specify scenarios (priority/limited-stop; trunk–feeder with timed transfers; frequency optimization under a fleet cap), and solve a theory-first optimization (GA/NSGA-II or ALNS) with equity-ready objectives and constraints. The resulting designs, KPIs, and accessibility maps will then be reported for Mid-Size City's 40/60 corridors in the practical chapter.

XI. DISCUSSION

Policy implications for Iraqi mid-sized cities center on organizing the scarce fleet around frequent trunks and engineered transfers. A frequency-first approach on two or three strongest corridors (e.g., an E–W and an N–S spine) reduces generalized door-to-door costs mainly through lower expected waiting times and more reliable connections. This requires a complementary stop policy (balanced spacing, far-side at signals, and selective lay-bys only where dwell times are systematically high), conditional TSP at critical junctions, and all-door/off-board fare collection to suppress dwell variability. A GTFS-native workflow enhances governance by making assumptions auditable and results reproducible—stakeholders can directly interrogate route alignments, stop sets, headways, and hub phasing in scenario feeds. Equity should be integrated upstream into the design problem through minimum accessibility floors for underserved zones, rather than remaining a downstream report. Finally, transferability is high: the same pipeline (L-/P-/Route-space diagnostics → GTFS scenarios → KPI and accessibility reporting) applies to similar Iraqi cities, with local calibration of boarding rates, transfer penalties, and pedestrian access conditions.

XII. CONCLUSION

This review assembles a theory-driven framework for bus network redesign and translates it into a reproducible, GTFS-backed workflow. By linking design levers—such as routes, frequency, stop spacing/placement, timed transfers, boarding method, and signal priority—to measurable mechanisms and outcomes, it provides a practical toolkit for agencies operating under tight budgets and mixed-traffic conditions. The KPI pack and equity-aware accessibility elevate reporting from anecdote to evidence. The framework is ready for empirical deployment in a mid-sized City, focusing on Streets in the city center with short feeders, and will be evaluated through scenario-based GTFS and standardized KPIs.

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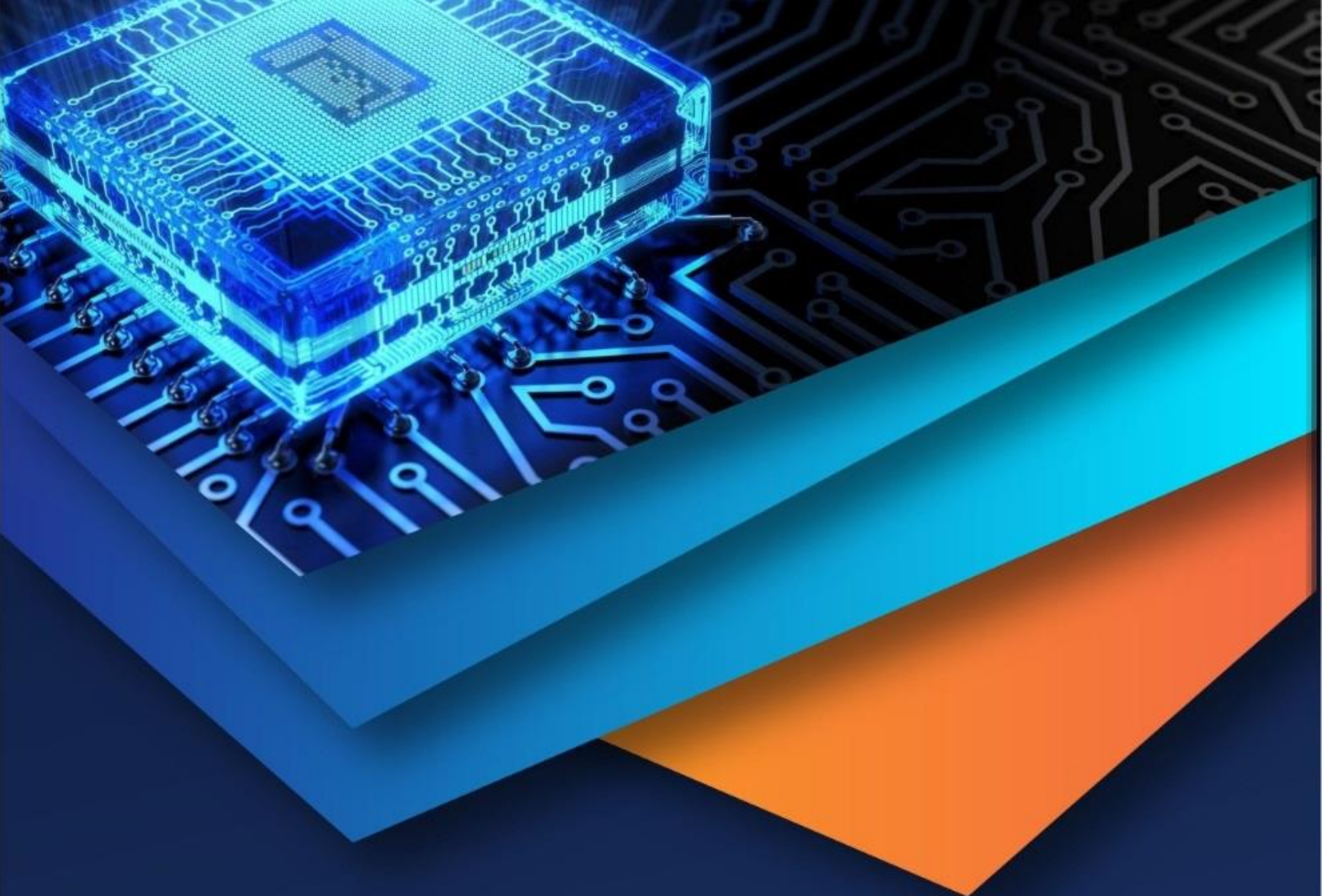

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