Ethics-Aware Multimodal Accessible Transit Design: Synergistic Optimization of Equity and Efficiency

1st Jiayi Chen
Macau University of Science and Technology University of Macau
Macau, China
songyuqian64@gmail.com

2nd Shuyi Zhang
Zhongkai University of Agriculture and Engineerin
Guangzhou, China
1019329043@qq.com

***Abstract*—In the pursuit of operational efficiency, urban transit systems frequently overlook equity across social groups, resulting in substantial accessibility disparities for vulnerable populations such as older adults, people with disabilities, and low-income residents. Although transport equity has gained increasing scholarly attention, existing research rarely embeds explicit ethical principles into the design and optimization of complex multimodal networks. In particular, the quantification and improvement of transfer accessibility remain underexplored, despite transfers being critical bottlenecks in multimodal travel chains. To address this gap, this study proposes an ethics-informed framework for multimodal accessible transit design. Drawing on and operationalizing John Rawls ' s Difference Principle, the framework adapts this normative concept to a networked transport context by formulating an optimization objective that prioritizes improvements in accessibility for the most disadvantaged groups. Rather than maximizing aggregate accessibility, the model seeks to enhance the minimum accessibility level within the system, thereby aligning network design with distributive justice principles. Using a major metropolitan area as a case study, the research constructs a comprehensive, reproducible multimodal transit network model integrating metro, bus, and bike-sharing systems. The model relies exclusively on publicly available data sources, including open transit schedules and stop data (e.g., GTFS or official timetables), open points-of-interest (POI) datasets, and aggregated demographic statistics. This data integration enables transparent modeling of travel times, transfer processes, and opportunity distributions across space. A key methodological contribution is the development of a transfer accessibility index that explicitly incorporates both physical barriers (e.g., walking distance, vertical circulation constraints) and temporal barriers (e.g., waiting time, schedule synchronization). By embedding this index into the optimization framework, the model captures the equity implications of transfer design — an often-overlooked dimension of accessibility measurement. Numerical experiments reveal that, under realistic conditions characterized by uneven spatial distribution of opportunities, conventional utilitarian optimization strategies tend to exacerbate accessibility inequality. In contrast, the Rawlsian difference-principle-based design substantially improves distributive outcomes, increasing accessibility for the most disadvantaged groups by more than 35%, while incurring a 10 – 15% reduction in overall system accessibility. These findings illustrate a measurable equity – efficiency trade-off and provide quantitative evidence of the redistributive potential of ethics-guided planning. Moreover, the results indicate that targeted improvements to transfer nodes represent a particularly effective lever for enhancing overall transport equity. Because transfer points function as critical connectors within multimodal systems, their design disproportionately affects accessibility outcomes for vulnerable users. Overall, this study contributes a theoretically grounded and operationally implementable methodology for embedding ethical reasoning into transit planning. By translating the difference principle into a formal optimization model and demonstrating its empirical implications, the research offers urban planners and policymakers a practical pathway for systematically integrating equity considerations into multimodal network design. In doing so, it advances the development of more inclusive and sustainable urban transit systems that balance efficiency with distributive justice.**

Keywords—Multimodal Transit; Accessible Design; Ethics-Aware; Equity and Efficiency; Difference Principle

I. Introduction

The development and prosperity of modern cities depend heavily on efficient and accessible public transit systems. Beyond serving as physical connectors between urban functional zones, these systems constitute a critical foundation for ensuring residents ' equal participation in social and economic activities [1]. Access to reliable transportation shapes individuals ' ability to reach employment, education, healthcare, and other essential services, thereby influencing broader patterns of opportunity and inclusion.

However, the dominant paradigm in transport planning has historically prioritized efficiency maximization—seeking to satisfy the greatest volume of travel demand at the lowest possible cost. While this utilitarian orientation has contributed to improvements in operational performance, it has often overlooked the equitable distribution of transport resources across different social groups [2]. As a result, transport inequality has become an increasingly salient concern.

Vulnerable populations — including older adults, people with disabilities, and low-income households — typically encounter greater physical, financial, and temporal barriers in their daily travel [3]. These barriers manifest in longer travel times, limited access to multimodal options, inadequate transfer facilities, and affordability constraints. The resulting accessibility gaps not only restrict access to essential public services but also deepen patterns of social exclusion and marginalization. Such outcomes stand in tension with the inclusive urban development vision embodied in the United

Corresponding Author: Jiayi Chen ,Wailong Road, Taipa, Macao, China, 999078, songyuqian64@gmail.com

Nations Sustainable Development Goals (SDGs), particularly the commitment to "leave no one behind" [4].

II. Literature Review

To establish a solid theoretical foundation and clarify the positioning of this study, this section systematically reviews prior research in four core areas: transport equity, ethical theories in transport planning, multimodal transit system design, and transfer accessibility. Based on this review, key research gaps are identified.

A. Transport Equity Research

Transport equity represents the application of social equity principles within the transportation domain. It concerns the just distribution of both benefits (e.g., accessibility) and burdens (e.g., fares, travel time, and environmental externalities) across social groups. Litman [5] distinguishes between horizontal equity and vertical equity. Horizontal equity emphasizes equal treatment of individuals or groups in similar circumstances, such as providing uniform service standards across neighborhoods. Vertical equity, by contrast, advocates differentiated treatment based on varying needs and abilities, prioritizing support for disadvantaged groups to achieve substantive equality of opportunity[6,7].

This study adopts a vertical equity perspective, aiming to compensate for mobility disadvantages experienced by vulnerable populations through differentiated transit design.

Accessibility has become the primary indicator for evaluating transport equity. It reflects the ease with which individuals can reach desired opportunities — such as employment, education, healthcare, and services — via the transport system [8,9]. Geurs and Van Wee [6] classify accessibility measures into four categories:

- Infrastructure-based measures (e.g., network density),
- Location-based measures (e.g., opportunities reachable within a time threshold),
- Person-based measures (accounting for individual heterogeneity), and
- Utility-based measures (incorporating behavioral preferences).

Among these, location-based measures — such as cumulative opportunity indicators — are widely used due to their intuitive interpretation and relatively modest data requirements [10,11]. However, two limitations persist. First, most accessibility studies focus on single modes and insufficiently capture the complexity of multimodal travel chains. Second, accessibility is typically used as an evaluation outcome rather than as a decision variable embedded within optimization models. This limits its potential as an active design instrument for promoting equity.

B. Ethical Theories in Transport Planning

Incorporating ethical theory into transport planning provides normative guidance for addressing distributional concerns. Several ethical frameworks have been discussed in the literature [12].

Utilitarianism, the implicit foundation of much traditional transport planning, seeks to maximize aggregate welfare — often operationalized as minimizing total travel time or maximizing total accessibility [13]. While analytically convenient and computationally tractable, utilitarian approaches overlook distributional fairness and may disadvantage vulnerable populations in pursuit of system-wide efficiency.

Egalitarianism emphasizes equality of outcomes, often operationalized through minimizing inequality metrics such as the Gini coefficient or variance in accessibility distribution [14]. However, strict egalitarian approaches may disregard differences in individual needs and risk inefficient resource allocation.

Sufficientarianism proposes that justice requires ensuring all individuals achieve a minimum acceptable threshold of resources or opportunities [15]. In transport terms, this implies guaranteeing a baseline level of accessibility. Yet defining and operationalizing a "sufficient" threshold remains methodologically and normatively challenging.

Rawls's Theory of Justice, particularly the Difference Principle, offers a more nuanced framework. It asserts that social and economic inequalities are permissible only if they benefit the least advantaged members of society [9]. Unlike egalitarianism, it allows inequality under specific conditions; unlike utilitarianism, it prioritizes the welfare of the least advantaged rather than aggregate outcomes. Martens et al. [16] pioneered the application of Rawlsian principles to transport planning, arguing that they provide a robust philosophical basis for vertical equity. However, as noted by Dai et al. [17], translating the Difference Principle from simplified corridor-based models to complex, multimodal urban networks remains an unresolved methodological challenge.

C. Multimodal Transit System Design

Designing multimodal transit systems involves complex network optimization across multiple decision layers, including route configuration, stop placement, service frequency, and fare structures [18]. Traditional approaches, such as the Network Design Problem (NDP), typically seek to optimize system performance by minimizing total cost or maximizing aggregate benefit [19]. These formulations largely reflect a utilitarian paradigm.

Transfers constitute a critical component of multimodal systems and significantly shape user experience, particularly for vulnerable populations. Existing transfer optimization research primarily focuses on reducing waiting times, walking distances, and the number of transfers [20]. While these dimensions are important, transfers are typically treated as generalized cost elements rather than as equity-sensitive accessibility constraints.

Moreover, physical and environmental features of transfer facilities — such as elevator availability, barrier-free pathways, and wayfinding design — are seldom incorporated into accessibility metrics or network optimization models. As a result, transfer-related barriers are insufficiently captured in equity analyses. The absence of a rigorous, quantifiable measure of "transfer accessibility" represents a significant limitation in current research.

D. Identification of Research Gaps

The preceding review reveals several critical gaps that motivate this study:

1) Gap Between Ethical Theory and Operational Design

Although ethical frameworks — particularly Rawls's Difference Principle — have been conceptually discussed in transport research, most applications remain theoretical or confined to highly simplified models. There is a lack of an integrated and operational framework capable of embedding ethical principles within real-world, complex multimodal network design.

2) Insufficient Multimodal Integration

Existing equity analyses often focus on single modes or simplified corridors. Such approaches neglect the networked and multimodal nature of urban mobility and fail to account for intermodal transfers and mode-switching behavior. This limits their relevance for comprehensive transport planning.

3) Neglect of Transfer Accessibility

Transfers represent a structural bottleneck in multimodal systems and disproportionately affect vulnerable users. However, current accessibility metrics and network design models rarely incorporate physical and environmental transfer barriers in a systematic manner. The absence of a robust transfer accessibility index constrains the ability to design equity-oriented networks.

4) Ambiguity in the Equity – Efficiency Trade-off

While the equity – efficiency trade-off is widely acknowledged, empirical quantification of this relationship within multimodal network contexts remains limited. In particular, the magnitude of efficiency loss associated with difference-principle-based designs — and the shape of the corresponding Pareto frontier—are insufficiently understood. This ambiguity restricts evidence-based policymaking.

a) Positioning of This Study

In response to these gaps, this study develops an ethics-aware multimodal transit design framework that operationalizes the Difference Principle within a realistic network context. By integrating accessibility measurement, transfer quantification, and equity-oriented optimization, the research seeks to advance theoretical understanding and provide a practically implementable methodology for embedding justice considerations into transit planning.

III. Related Work

This section reviews three methodological domains directly related to the technical foundation of this study: accessibility measurement, transit network design optimization, and transport planning models incorporating equity constraints. By critically examining existing approaches, this section clarifies the methodological distinctiveness and innovation of the proposed framework.

A. Accessibility Measurement Research

Accessibility quantification forms the analytical foundation of transport equity research. Among the various approaches, location-based measures are widely adopted due to their intuitive representation of spatio-temporal relationships between individuals and opportunities. Two classical models dominate this domain: the gravity-based model proposed by Hansen [21] and the cumulative-opportunity model represented by Cervero et al. [22].

The gravity model incorporates a distance-decay function to discount opportunity attractiveness as travel cost increases, thereby capturing continuous accessibility variation. In contrast, the cumulative-opportunity model calculates the number of opportunities reachable within a specified travel time or cost threshold. Due to its transparency and policy interpretability, the cumulative-opportunity approach is particularly suitable for distributive justice analysis. Moreover, its focus on reachable "primary goods" aligns conceptually with Rawlsian principles [17]. For these reasons, this study adopts the cumulative-opportunity framework as its analytical base.

However, applying classical accessibility models to multimodal networks introduces substantial challenges. Most existing studies simplify transfer processes by assigning a fixed penalty constant to represent transfer costs [23]. Such treatment overlooks the heterogeneity and structural complexity of transfers. A cross-platform transfer within the same station differs fundamentally from a transfer requiring long walking distances, vertical movement, or the absence of barrier-free facilities — especially for elderly or mobility-impaired users.

Recent research has introduced more refined transfer representations. For example, Nassir et al. [24] incorporated walking time, waiting time, and reliability into path-choice modeling. Nevertheless, these efforts primarily aim to improve behavioral realism rather than to embed transfer accessibility into equity-oriented network design optimization. A key methodological contribution of this study is the development of a comprehensive transfer accessibility index that integrates physical infrastructure conditions, temporal costs, and convenience factors, and operationalizes this index as an endogenous variable within an equity-driven optimization model.

B. Transit Network Design Optimization

The Transit Network Design Problem (TNDP) is a classical combinatorial optimization problem concerned with determining optimal route alignments, stop configurations, and service frequencies to improve network performance [18]. Depending on the objective function, TNDP formulations typically pursue either:

- System-optimal solutions, minimizing operator costs; or
- User-optimal solutions, minimizing aggregate travel time.
- Both formulations largely reflect utilitarian logic centered on aggregate performance.

Given its NP-hard nature, TNDP has been addressed using various heuristic and meta-heuristic algorithms, including Genetic Algorithms (GA), Simulated Annealing (SA), and Tabu Search (TS) [25]. With increased computational power, exact algorithms and Mixed-Integer Programming (MIP) approaches have also been applied to small- and medium-scale problems.

Despite methodological sophistication, most TNDP studies restrict decision variables to macro-level service parameters such as route structures and frequencies. Infrastructure-level design elements — particularly accessibility-related facilities at transfer nodes — are rarely treated as decision variables.

This study extends the TNDP framework in two important ways. First, it incorporates micro-level infrastructure interventions, such as the installation or upgrading of elevators, ramps, and barrier-free pathways at transfer stations, into the optimization decision space. Second, it explicitly links these infrastructure decisions to accessibility outcomes for vulnerable groups. By bridging service-level planning and infrastructure-level design, the model deepens the integration of equity considerations into network optimization.

C. Transport Planning Models with Explicit Equity Constraints

To move beyond utilitarian optimization, scholars have begun incorporating equity considerations directly into planning models. One common approach introduces equity as a constraint. For example, Talebian and Mishan [7] imposed minimum service frequency constraints to ensure baseline coverage, reflecting sufficientarian principles.

Another approach treats equity as an explicit objective. Verma et al. [8] proposed a multi-objective model minimizing the accessibility Gini coefficient. While intuitive, aggregate inequality metrics such as the Gini coefficient may obscure improvements (or deteriorations) experienced by specific vulnerable groups.

The application of Rawls ’ s Difference Principle represents an emerging direction. Dai et al. [17] formulated a maximin optimization model for a simplified linear bus corridor, demonstrating analytically that difference-principle-based designs can diverge significantly from utilitarian outcomes. Related work in facility location problems has applied the maximin criterion in a similar spirit [26].

However, two limitations persist in this stream of research. First, most applications focus on single-mode or simplified network structures, limiting realism. Second, definitions of the “ least advantaged ” are often geographically simplistic, typically identifying residents in peripheral or remote areas without accounting for multidimensional socioeconomic vulnerability.

In contrast, this study operationalizes the Difference Principle within a multimodal urban network and identifies disadvantaged groups using multidimensional indicators derived from publicly available demographic and mobility-related data (e.g., income, age structure, mobility constraints) [27]. This approach enhances both ethical precision and empirical relevance.

D. Methodological Innovation and Positioning

This study builds upon, but moves beyond, existing research in accessibility measurement, network design optimization, and equity modeling. Its methodological innovations can be summarized as follows:

1) Refined Transfer Accessibility Quantification

Development of a comprehensive transfer accessibility index incorporating physical infrastructure conditions, temporal costs, and convenience factors.

2) Integration of Micro-Level Infrastructure Decisions

Extension of traditional TNDP by including accessibility facility investments at transfer nodes as endogenous decision variables.

3) Operationalization of the Difference Principle in a Multimodal Context

Embedding a Rawlsian maximin objective within a realistic multimodal network framework using reproducible public data.

4) Multidimensional Identification of Vulnerable Groups

Defining the “ least advantaged ” not solely by geographic location but by socioeconomic and mobility attributes.

Through this integrated technical pathway, the study advances methodological rigor and ethical operationalization in multimodal transit design. It demonstrates how refined accessibility modeling, infrastructure-level decision integration, and justice-oriented optimization can be systematically combined within a unified analytical framework.

IV. Methodology

The core objective of this research is to construct a mathematical framework capable of endogenizing ethical principles within the design of multimodal transit networks. To achieve this, the study proceeds in two stages.

First, a comprehensive accessibility quantification method is developed to capture the structural and experiential complexity of multimodal travel, particularly the physical and temporal characteristics of transfer processes. This method extends conventional accessibility measures by incorporating detailed representations of intermodal interactions and transfer-related barriers, thereby providing a more realistic basis for equity-oriented evaluation.

Second, building upon this accessibility framework, four optimization models are formulated, each corresponding to a distinct ethical perspective: utilitarianism, egalitarianism, sufficientarianism, and Rawls ’ s difference principle. Among these, particular emphasis is placed on the model grounded in the Difference Principle, which seeks to maximize the accessibility level of the least advantaged groups within the network.

This chapter systematically presents the technical route and model construction process, including accessibility formulation, ethical objective specification, decision variable definition, and optimization structure. Through this structured modeling approach, ethical reasoning is translated into operational design mechanisms within a multimodal transit planning context.

A. Research Strategy

This study adopts a research strategy that combines theoretical modeling and numerical experiments. The overall technical route is shown in Figure 1.

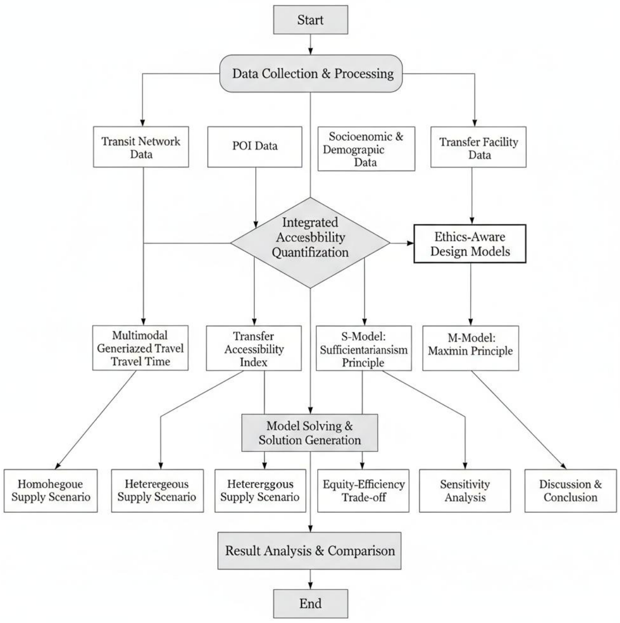

Fig. 1. *Research Framework Flowchart*

First, the multimodal transit network of the study area is formally defined as a layered graph structure, in which each layer corresponds to a distinct transport mode (metro, bus, and bike-sharing). Nodes represent transit stations and opportunity points (e.g., POIs), while edges denote intra-modal travel links and inter-modal transfer connections. This multilayer representation enables explicit modeling of modal interactions and transfer processes within a unified network topology.

Second, publicly available and reproducible datasets are collected and processed to parameterize the model. These datasets include transit network data (e.g., routes, schedules, stop locations), POI data reflecting spatial opportunity distribution, and aggregated demographic and socioeconomic indicators used to characterize population groups. Data preprocessing involves network construction, travel-time estimation, transfer attribute extraction, and spatial aggregation to appropriate analytical units. These inputs provide the empirical foundation for model calibration and scenario evaluation.

Third, a comprehensive accessibility quantification model is constructed to compute integrated accessibility from any individual or spatial unit to the full set of opportunity points within the network. The model incorporates multimodal travel times, transfer penalties, and transfer accessibility attributes, thereby generating an accessibility metric sensitive to both temporal and physical constraints.

Finally, the accessibility model is embedded within four ethics-aware optimization frameworks, each corresponding to a distinct normative principle. These frameworks treat accessibility outcomes as objective functions or constraints, depending on the ethical orientation. By solving the resulting optimization problems, the study derives ethically differentiated transit resource allocation schemes, including adjustments to service frequencies and investments in transfer facility improvements. The comparative performance of these schemes — particularly in terms of equity and efficiency trade-offs — is analyzed in subsequent chapters.

B. *Comprehensive Accessibility Quantification Method*

We adopt the cumulative-opportunity model as the foundational framework for accessibility quantification. Under this approach, the accessibility A_i of an individual (or spatial unit) *i* is defined as the total quantity of opportunities that can be reached from its origin within a specified travel time budget *T*. Let *O* denote the set of all opportunity points (e.g., employment centers, schools, healthcare facilities), and let t_{ij} represent the generalized travel time from origin *i* to opportunity location *j*. An opportunity *j* is considered reachable if $t_{ij} \le T^{'}$. The magnitude of opportunity at location *j*, denoted by S_j, may be weighted according to its type, scale, or service capacity (e.g., number of jobs, hospital beds, retail floor area).

Accordingly, the cumulative accessibility of individual *i* can be expressed in its basic form as:

$$A_i = \sum_{j\in O} S_j \cdot 1(t_{ij} \le T) \tag{1}$$

1) *Generalized Travel Time in a Multimodal Network*

In the cumulative-opportunity formulation, w_j denotes the weight of opportunity point *j* (reflecting its type and scale). The key methodological issue is how to compute the generalized travel time c_{ij} from origin *i* to opportunity *j* so that it faithfully reflects multimodal travel experience, especially transfer-related barriers.

Let P_{ij} be the set of all feasible multimodal paths from *i* to *j*. We define c_{ij} as the minimum generalized travel time over all feasible paths:

$$c_{ij} = \min_{p\in P_{ij}} \left(\sum_{e\in p} t_e^{travel} + \sum_{k\in \mathcal{K}(p)} t_k^{wait} + \sum_{m\in \mathcal{M}(p)} t_m^{transfer} \right) \tag{2}$$

where:

- t_e^{travel} is the in-vehicle travel time on link
- t_k^{wait} is the waiting time incurred at transfer (or boarding) node k_1, commonly approximated as half the service headway;
- $t_m^{transfer}$ is the generalized transfer time at transfer node m, which constitutes the key innovation of this study.

In contrast to conventional approaches that treat transfers as a fixed penalty, $t_m^{transfer}$ is designed to capture heterogeneous transfer barriers (e.g., walking distance, vertical circulation, accessibility facilities, and other physical/environmental constraints). The next subsection specifies the structure of $t_m^{transfer}$ and how it connects to transfer facility improvement decisions in the optimization model.

2) *Quantification of Transfer Accessibility*

We decompose the generalized transfer time $t_m^{transfer}$ into three components:

$$t_m^{transfer} = t_m^{walk} + t_m^{facility} + t_m^{info} \tag{3}$$

where:

- t_m^{walk} denotes the transfer walking time, determined by the physical length and configuration of the transfer passage;
- $t_m^{facility}$ represents the facility barrier penalty time, which constitutes a key policy-sensitive component;
- t_m^{info} captures delays caused by informational uncertainty, such as unclear signage or insufficient real-time guidance.

3) Facility Barrier Penalty as a Decision-Dependent Component

To explicitly model the effect of accessibility investments, we introduce a binary decision variable: $x_m \in \{0,1\}$

where:

- $x_m = 1$ indicates investment in accessible facility improvements at transfer station
- $x_m = 0$ represents maintaining the existing infrastructure conditions.

The facility barrier penalty time is then defined as:

$$t_m^{facility} = \alpha_g (1 - x_m)\delta_m, \quad x_m \in \{0,1\} \tag{4}$$

where:

- δ_m denotes the baseline degree of physical barriers at station m, which may be quantified using publicly available station design standards, operator accessibility disclosures, or clearly specified scenario-based parameters to ensure reproducibility;
- α_g is the sensitivity coefficient of group g (e.g., elderly individuals or persons with disabilities) to physical barriers.

The coefficient α_g captures heterogeneous vulnerability. A larger value implies that the group incurs a higher generalized time penalty when encountering physical barriers. For the general population, α_g may be set to zero, implying no additional barrier-induced time cost. This formulation enables transfer facility investments to differentially affect accessibility outcomes across social groups, thereby directly embedding vertical equity considerations into the model.

4) Information Uncertainty Component

The term t_m^{info} represents delays caused by informational deficiencies (e.g., inadequate wayfinding systems or schedule uncertainty). In the current study, this component is treated as a constant parameter. However, it provides a natural extension point for future research incorporating dynamic information systems or smart guidance technologies.

Through these formulations, the comprehensive accessibility measure A_i becomes a function not only of spatial location but also of:

- service-level variables (e.g., headways influencing t_k^{wait}), and
- infrastructure investment decisions (e.g., x_m).

Consequently, accessibility is transformed from a passive evaluation indicator into an endogenous outcome of transit system design. This functional dependence provides a direct analytical lever for the subsequent ethics-aware optimization models.

C. Ethics-Aware Design Models

We construct four optimization models corresponding to utilitarianism (U-Model), sufficientarianism (S-Model), the maximin principle (MM-Model), and Rawls ' s difference principle (D-Model). All models share a common resource budget constraint:

$$\sum_{l \in L} C_l(f_l) + \sum_{m \in M} C_m(x_m) \leq B \tag{5}$$

where:

- f_l is the service frequency of route $l \in L$;
- $C_l(f_l)$ denotes the operating cost associated with frequency f_l
- $x_m \in \{0,1\}$ represents the accessible facility improvement decision at transfer station $m \in M$;
- $C_m(x_m)$ is the corresponding infrastructure investment cost;
- B is the total available budget.

Let:

- I denote the set of individuals (or traffic analysis zones);
- P_i denote the population of unit i;
- $A_i(f, x)$ denote the accessibility of unit i, determined by decision vectors f and x.

1) Utilitarian Model (U-Model)

The utilitarian model maximizes total (population-weighted) accessibility across society, reflecting the principle of maximizing aggregate welfare:

$$\max_{f,x} \sum_{i \in I} P_i A_i(f, x) \tag{6}$$

subject to the common budget constraint (5).

This formulation prioritizes overall system efficiency but does not explicitly account for distributive fairness.

2) Sufficientarian Model (S-Model)

The sufficientarian model ensures that every individual achieves at least a minimum accessibility threshold $A_{\min}$, reflecting the principle of guaranteeing basic mobility rights.

A standard formulation is:

$$\max_{f,x} \sum_{i \in I} P_i A_i(f, x)$$

subject to:

$$A_i(f, x) \geq A_{min} \quad , \ \forall i \in I$$

$$\sum_{l \in L} C_l(f_l) + \sum_{m \in M} C_m(x_m) \leq B$$

(7)

subject to the budget constraint (5).

This model improves the accessibility of the worst-off individual (or zone) regardless of socioeconomic identity. However, it does not explicitly define disadvantage in social or demographic terms. The "worst-off" unit is determined purely by accessibility level.

3) Maximin Principle Model (MM-Model)

The Difference Principle Model constitutes the core contribution of this study. Unlike the MM-Model, it explicitly identifies a least advantaged group $G \subseteq I$ based on multidimensional socioeconomic indicators (e.g., income level, age structure, disability prevalence). These groups are identified using aggregated public statistics and reproducible classification methods (e.g., clustering or rule-based screening).

Let:

- G denote the predefined set of least advantaged units;
- P_g denote the population of unit $g \in G$;
- $A_g(f, x)$ denote the accessibility of unit g.

The objective is to maximize the population-weighted average accessibility of the least advantaged group:

$$\max_{f,x} \frac{\sum_{g \in G} P_g A_g(f,x)}{\sum_{g \in G} P_g} \tag{8}$$

subject to the budget constraint (5).

This formulation operationalizes Rawls's Difference Principle by directing optimization explicitly toward improving the well-being of the least advantaged group, rather than simply raising the minimum accessibility value across all units.

4) Conceptual Distinction Among Models

- U-Model: Maximizes aggregate welfare (efficiency-oriented).
- S-Model: Guarantees a minimum accessibility floor (basic rights orientation).
- MM-Model: Maximizes the accessibility of the worst-off unit (accessibility-based maximin).
- D-Model: Maximizes the accessibility of a socioeconomically defined least advantaged group (Rawlsian justice orientation).

By solving these four models under identical budget constraints and network conditions, the study enables systematic comparison of equity – efficiency trade-offs and clarifies the practical implications of different ethical principles in multimodal transit design.

5) Difference Principle Model (D-Model)

This model constitutes the core contribution of this study. It explicitly directs optimization toward improving the well-being of the least advantaged group, rather than focusing on aggregate performance or purely accessibility-based disadvantage.

a) Identification of the Least Advantaged Group

The first step is to identify the set $G \subseteq I_r$, representing the least advantaged group. In this study, group identification is based on multidimensional socioeconomic characteristics rather than solely on spatial accessibility outcomes.

Specifically, we consider aggregated public and reproducible indicators such as:

- median income level,
- age structure (e.g., proportion of elderly residents),
- disability prevalence,
- and other openly available socioeconomic proxy variables.

Using cluster analysis or transparent rule-based classification methods applied to district- or subdistrict-level statistics, we identify those spatial units that are socioeconomically most disadvantaged. The resulting subset G is fixed prior to optimization and remains exogenous to the decision variables.

b) Objective Function

Let:

P_g denote the population of unit $g \in G$

$A_g(f, x)$ denote the accessibility of unit g, determined by service frequency decisions f and facility investment decisions x.

The objective of the Difference Principle Model is to maximize the population-weighted average accessibility of the least advantaged group:

$$\max_{f,x} \frac{\sum_{g \in G} P_g A_g(f,x)}{\sum_{g \in G} P_g} \tag{9}$$

subject to the common budget constraint:

$$\sum_{l \in L} C_l(f_l) + \sum_{m \in M} C_m(x_m) \leq B \tag{10}$$

c) Normative Interpretation

This formulation directly operationalizes Rawls's Difference Principle, which holds that social and economic inequalities are justifiable only if they are arranged to the greatest benefit of the least advantaged members of society. In this model:

- Resource allocation is not evaluated by total accessibility (as in utilitarianism),
- Nor by the minimum accessibility level across all units (as in the maximin model),
- But by its impact on a socioeconomically defined vulnerable group.

By solving the D-Model, we obtain a transit resource allocation scheme — covering both service-level decisions (e.g., frequency adjustments) and infrastructure investments (e.g., transfer facility upgrades) — that systematically prioritizes improvements for vulnerable populations.

This design ensures that ethical reasoning is not merely discussed normatively but is structurally embedded within the optimization framework itself.

V. Data and Study Area

To operationalize and empirically evaluate the proposed theoretical models, this study selects the core urban area of a major Chinese city (hereafter referred to as "City M" for confidentiality) as the case study. This chapter presents an overview of the study area, describes data sources and preprocessing procedures, and reports key descriptive statistics that underpin the subsequent modeling and optimization analysis.

A. *Study Area Overview*

The core urban area of City M spans approximately 150 square kilometers and accommodates a resident population of roughly 3 million. As the political, economic, and cultural center of the city, this area exhibits high-density, mixed-use land development. Employment centers, commercial districts, healthcare institutions, and educational facilities are densely clustered, generating substantial and spatially diverse travel demand.

The multimodal transit system within the study area is highly developed. It consists of:

- A dense metro network comprising 10 operational lines
- An extensive conventional bus system providing fine-grained surface coverage,
- A high-density bike-sharing system operated by multiple providers.

The integration of these modes forms a complex, layered urban mobility network characterized by frequent transfers and multimodal travel chains.

Despite the apparent maturity of transport infrastructure, significant accessibility disparities remain. These disparities stem from uneven spatial distributions of population, employment opportunities, and public service facilities, as well as variations in transfer convenience and service frequency. Moreover, socioeconomic heterogeneity across districts amplifies differences in effective accessibility experienced by vulnerable groups.

The coexistence of advanced multimodal infrastructure and persistent accessibility inequality makes City M's core urban area a suitable and representative context for testing the proposed ethics-aware transit design framework. Figure 2 illustrates the schematic structure of the multimodal network in the study area.

Figure 2: Schematic of Multimodal Transit Network in Study Area

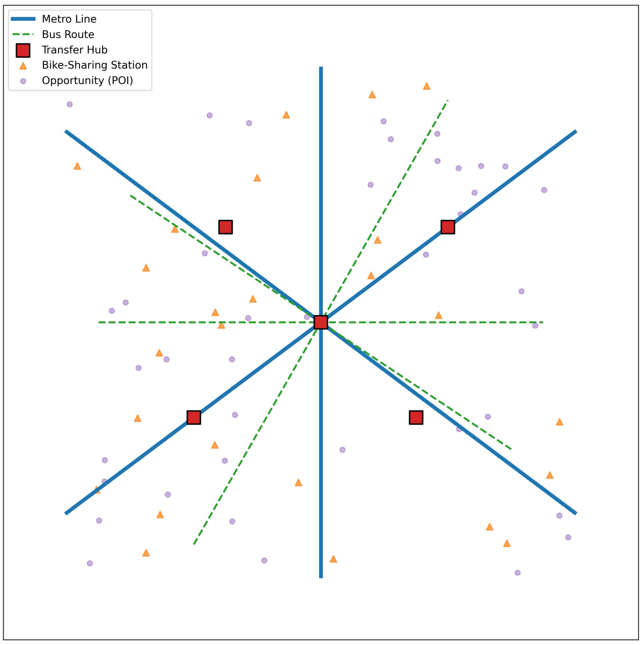

Fig. 2. *Schematic of Multimodal Transit Network in Study Are*

B. *Data Sources*

This study relies exclusively on publicly available and reproducible datasets to construct an operational representation of the city's transport and socioeconomic structure. The primary data sources are as follows:

1) *Transit Network Data*

Transit network data were obtained from open and publicly accessible sources, including:

- General Transit Feed Specification (GTFS) feeds and published timetables,
- Open-data portals released by local authorities,
- OpenStreetMap (OSM) for route alignments and stop locations,
- Publicly accessible bike-sharing feeds (e.g., GBFS) where available.

These datasets provide detailed information on metro and bus routes, stop locations, service schedules, and network topology within the study area. For bike-sharing systems, station locations and availability data were incorporated when accessible through open feeds.

2) *Population and Socioeconomic Data*

Population and socioeconomic information was derived from publicly released census aggregates, statistical yearbooks, and open government reports. These datasets provide:

- Population counts,
- Age structure (e.g., proportion of elderly residents),
- Income-related indicators or other socioeconomic proxies,

at aggregated administrative levels (e.g., district or subdistrict). Where finer-resolution census data (e.g., census blocks) were publicly accessible, they were used to enhance spatial precision.

The use of aggregated, publicly released statistics ensures methodological transparency and reproducibility while remaining consistent with typical data-access conditions in transport planning research.

3) Transfer Facility Data

Detailed transfer-facility attributes are often unavailable in open datasets. To address this limitation while maintaining reproducibility, we adopt a two-pronged strategy:

- When available, we incorporate publicly disclosed accessibility information and official design standards provided by transit operators;
- When such data are unavailable, we define explicit scenario-based transfer-penalty parameters grounded in documented design guidelines and literature benchmarks.

This approach avoids reliance on in-person field surveys and allows replication by other researchers. Robustness of the results is evaluated through systematic sensitivity analysis of key transfer-related parameters.

C. Data Preprocessing

1) Multimodal Network Construction

A multilayer transit network graph was constructed in which:

- Nodes represent transit stops, bike-sharing stations, and opportunity points (POIs).
- Edges represent in-vehicle travel links, walking connections, cycling links, and transfer connections.

All spatial elements were geocoded and topologically connected to ensure network continuity across modes. Service frequencies were converted into headways to calculate waiting times used in generalized travel cost estimation.

2) Opportunity Classification and Weighting

Points of interest (POIs) were categorized into functional groups (e.g., employment, healthcare, education). Opportunity weights were assigned based on transparent and verifiable rules. For example:

- Large general hospitals were assigned higher weights than small clinics,
- Employment opportunities were proxied using reproducible indicators such as POI category counts, publicly available size information, or standardized weights reported in the literature.

This standardized weighting scheme ensures comparability and reproducibility across scenarios.

3) Identification of the Least Advantaged Group

Based on aggregated public demographic and socioeconomic statistics, the least advantaged group G was defined as administrative units meeting both of the following criteria:

- The proportion of residents aged 65 and above falls within the top 20% quantile;
- The income-related indicator falls within the bottom 20% quantile (based on the most reliable publicly available proxy).

This operational definition targets low-income elderly populations — a group widely recognized as vulnerable in urban mobility contexts — while remaining feasible under realistic data-access constraints.

4) Parameter Calibration

The group sensitivity coefficient α_g for elderly individuals was calibrated using findings from empirical studies on walking speeds and mobility limitations across age groups. Specifically, the parameter was set such that climbing a standard flight of stairs corresponds to an additional generalized travel-time cost of approximately 30 seconds for elderly users. This calibration anchors the transfer-penalty parameter in documented behavioral evidence while maintaining transparency.

VI. Experiment Design and Results

This chapter presents the results of our numerical experiments based on the models and data described earlier. We begin by outlining the overall experimental setup. Next, we compare and analyze different transit network design strategies guided by four ethical principles, examining both homogeneous and heterogeneous supply scenarios. Finally, we assess the model ' s robustness through sensitivity analysis.

A. Experimental Setup

1) Baseline Scenario

We use the current transit network of City M's core urban area as the baseline. Service frequencies are based on off-peak timetable data, specifically from 10:00 AM to 4:00 PM. At this stage, the decision variables for enhancing accessible facilities, denoted as x_m, are set to zero for all transfer stations. The total budget, B, is defined as a normalized or scenario-based investment level—such as a fixed percentage of a baseline budget — allowing the experiment to be replicated without needing confidential cost data.

In this baseline scenario, we begin by assessing the current network ' s accessibility levels and how they are distributed spatially. This evaluation serves as a benchmark for comparing subsequent optimized designs. Figure 3 illustrates the current accessibility distribution, which reveals a distinct concentric pattern: accessibility decreases outward from the city center. Areas with high accessibility often overlap with major employment and commercial zones.

2) Design Scenarios

Working within the constraint of total budget B, we apply four ethically informed models to derive optimal resource allocation plans. The decision variables include bus route service frequencies (f_l), which can vary by ± 20% from current levels, and the improvements to accessible facilities (x_m) at metro transfer stations. We use a genetic algorithm to solve each model, with a population size of 100 and 500 iterations.

- U-Design: Based on the Utilitarian model (U-Model), this design seeks to maximize overall accessibility across the network.
- S-Design: Rooted in the Sufficientarian model (S-Model), this design sets a minimum accessibility threshold (A_{min}) at 110% of the current network's average for the most disadvantaged group.

- MM-Design: Guided by the Maximin principle (MM-Model), this approach aims to raise the accessibility of the spatial unit with the lowest current accessibility.
- D-Design: Based on the Difference principle model (D-Model), this design focuses on maximizing the average accessibility for the least advantaged group.

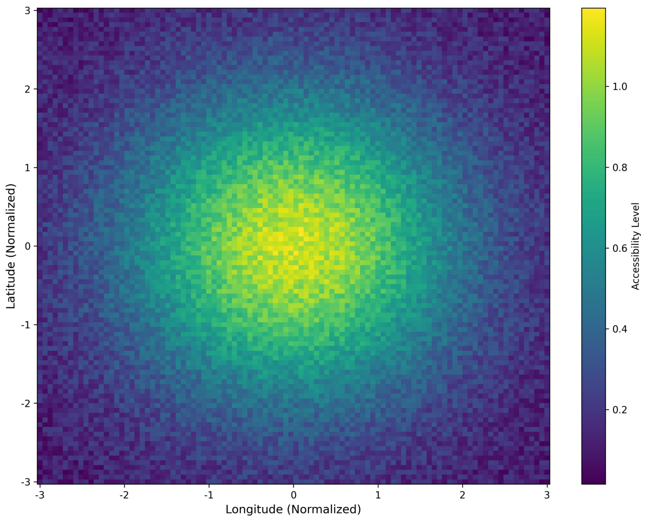

Fig. 3. *Spatial Distribution of Baseline Accessibility*

B. *Results Analysis in a Homogeneous Supply Scenario*

To evaluate how the different ethical principles perform under idealized conditions, we first constructed a virtual homogeneous supply scenario. In this setting, all opportunity locations are assumed to be evenly distributed across the study area, and all bus routes start with identical service frequencies.

The results show that, under these highly simplified and uniform conditions, the four design strategies—U-Design, S-Design, MM-Design, and D-Design—produce very similar resource allocation patterns. Consequently, the resulting accessibility distributions are nearly indistinguishable (see Table I).

This outcome aligns with the findings of Dai et al. [17] in their single-corridor model. When both system resources and travel demand are perfectly homogeneous in space, different ethical principles may ultimately lead to the same design solution. In such cases, the objectives of "equity" and "efficiency" do not conflict but instead coincide.

These findings suggest that spatial heterogeneity is a crucial precondition for ethical principles to generate meaningfully differentiated design outcomes. Without variation in spatial structure, the practical distinctions between ethical frameworks tend to diminish.

C. *Results Analysis in a Heterogeneous Supply Scenario*

We then shift back to a heterogeneous supply scenario built using publicly available and reproducible data for City M (or a comparable illustrative study area). This scenario represents the central focus of our analysis, as it reflects more realistic spatial variations in demand and service provision.

Figure 4 compares the performance of the four design strategies across three key evaluation metrics: overall system accessibility, the average accessibility of the least advantaged group, and the Gini coefficient measuring inequality in accessibility distribution. To provide a more comprehensive view, Table II presents a detailed breakdown of these performance indicators for each design scheme.

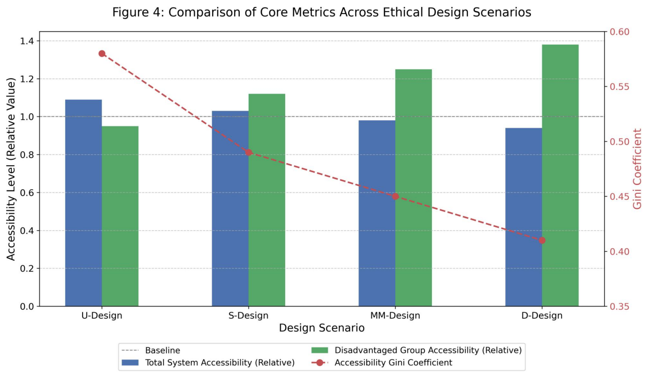

Fig. 4. *Comparison of Core Metrics Across Ethical Design Scenarios*

TABLE I. PERFORMANCE INDICATOR COMPARISON OF DIFFERENT DESIGN SCENARIOS

Indicator	Baseline	U-Design	S-Design	MM-Design	D-Design
Total System Accessibility	1.00 (Ref)	1.09 (+9%)	1.03 (+3%)	0.98 (-2%)	0.94 (-6%)
Least Advantaged Group Avg. Accessibility	1.00 (Ref)	0.95 (-5%)	1.12 (+12%)	1.25 (+25%)	1.38 (+38%)
Accessibility Gini Coefficient	0.52	0.58 (+11.5%)	0.49 (-5.8%)	0.45 (-13.5%)	0.41 (-21.2%)
Avg. Accessibility of Bottom 10% Pop.	1.00 (Ref)	0.88 (-12%)	1.08 (+8%)	1.31 (+31%)	1.27 (+27%)
Investment Ratio for Transfer Facilities	0%	15%	35%	55%	60%

Several important insights emerge from the results:

- Utilitarian Design Exacerbates Inequality: The U-Design, which seeks to maximize total system accessibility, tends to allocate more resources—particularly higher service frequencies—to central areas that already enjoy relatively high accessibility. Because these areas have greater population density and a higher concentration of opportunities, investments there generate the largest aggregate returns. As a result, overall system accessibility increases by 9%. However, this gain comes at a social cost: the accessibility of the least advantaged group declines by 5%, and the Gini coefficient rises from 0.52 to 0.58, indicating a marked increase in inequality.
- Difference Principle Design Significantly Improves Equity: In sharp contrast, the D-Design prioritizes improvements for the least advantaged group. Its main strategies include: (1) increasing bus service frequencies around residential areas where the least advantaged group is concentrated; and(2) directing

investment toward enhancing accessible facilities at key transfer nodes along their primary travel routes. This approach leads to a substantial 38% increase in the average accessibility of the least advantaged group and reduces the Gini coefficient significantly to 0.41. These results clearly demonstrate the effectiveness of the difference principle as a "bottom-line" design philosophy for advancing transport equity.

- Subtle Differences Among Equity-Oriented Principles: The S-Design and MM-Design, both equity-focused approaches, fall between U-Design and D-Design in terms of performance. The S-Design ensures a minimum accessibility threshold, leading to moderate equity gains, though the overall effect is limited. The MM-Design, grounded in the maximin principle, concentrates on improving conditions in the spatial unit with the lowest accessibility — often located in geographically remote areas. Its equity-enhancing impact is stronger than that of the S-Design but slightly weaker than that of the D-Design. This difference arises because the D-Design defines the "least advantaged group" using socioeconomic characteristics rather than purely spatial criteria. Since disadvantaged populations are not always located at the geographic periphery, the D-Design's objective is more closely aligned with social realities and therefore achieves more targeted equity improvements.

D. The Equity-Efficiency Trade-off

The results above clearly highlight the inherent trade-off between equity and efficiency. While the D-Design achieves the strongest equity outcomes, it reduces total system accessibility by 6% relative to the baseline and by approximately 14% compared with the U-Design. This decline in overall efficiency represents the cost of pursuing a higher level of distributive fairness.

To better capture and visualize this trade-off, we introduce a weight parameter into the D-Model that balances two competing objectives: maximizing the accessibility of the least advantaged group and maximizing total system accessibility. By varying this parameter, we generate the equity – efficiency Pareto frontier shown in Figure 5.

This curve represents the full set of optimal trade-off solutions. Each point along the frontier corresponds to a design scheme in which efficiency (total system accessibility) is maximized for a given level of equity (accessibility of the least advantaged group). In other words, moving along the curve improves one objective only at the expense of the other—there are no "free" gains beyond this boundary.

The Pareto frontier thus provides decision-makers with a clear and practical "menu" of policy options. Depending on their normative priorities, they can select an acceptable degree of efficiency loss and identify the corresponding optimal design. For instance, a policymaker might opt for a solution that captures 80% of the maximum possible equity improvement while incurring only a 5% reduction in overall efficiency.

In this way, the Pareto frontier translates what might otherwise be an abstract ethical dilemma into a concrete and quantifiable policy choice.

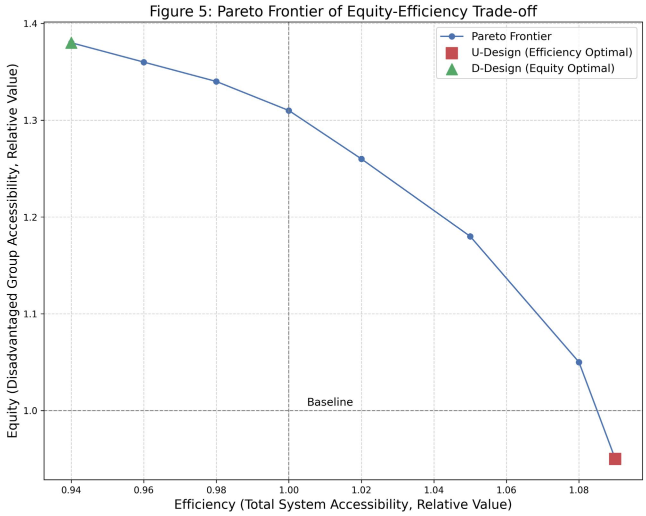

Fig. 5. *Pareto Frontier of Equity-Efficiency Trade-off*

E. Sensitivity Analysis

To examine the robustness of our findings, we conducted two sets of sensitivity analyses:

- Budget Level Variation: We adjusted the total budget B by −20% and +20% relative to its baseline level. The results indicate that, across all budget scenarios, D-Design consistently outperforms U-Design in terms of equity. Moreover, as the budget becomes more constrained, the tendency of U-Design to prioritize efficiency at the expense of equity becomes even more pronounced. This suggests that the difference principle is particularly relevant in resource-scarce contexts, where allocation choices are more consequential and equity risks being overlooked.
- Variation in Sensitivity to Transfer Barriers: We also modified the sensitivity coefficient α_g, which reflects how strongly the least advantaged group is affected by physical transfer barriers. As α_g increases, the D-Design allocates a substantially larger share of investment toward improving transfer facilities. Correspondingly, the gains in accessibility for the least advantaged group become more significant. These results provide quantitative evidence that enhancing transfer accessibility is a highly effective intervention for promoting transport equity — especially for mobility-impaired populations such as older adults and individuals with disabilities.

VII. Discussion

A. Interpretation of Results and Insights

The most fundamental insight of this research is that spatial heterogeneity acts as the catalyst that activates the differentiated effects of ethical principles. In the hypothetical homogeneous supply scenario, the various ethics-guided design schemes largely converged. This suggests that when resources and demand are perfectly aligned in space, tensions between equity and efficiency remain muted.

However, real cities are far from homogeneous. Employment, healthcare, and other opportunities are unevenly distributed, as are population groups with different socioeconomic characteristics. This structural unevenness is the root cause of transport inequality.

The utilitarian design (U-Design) follows a market-oriented logic, allocating resources to central areas where returns are highest. In practice, this resembles "adding flowers to a brocade" —enhancing areas that are already well served. The result is cumulative advantage: high-accessibility areas benefit further, while disadvantaged areas fall further behind, amplifying a systemic "Matthew effect."

In contrast, the difference principle design (D-Design) represents a compensatory, redistributive intervention. It deliberately directs resources toward disadvantaged groups and underserved areas—akin to "sending charcoal in snowy weather." Although this approach entails some loss in total system efficiency, it secures a more fundamental social value: protecting the basic mobility rights of society's most disadvantaged members and fostering broader social integration.

Another key insight concerns the leverage effect of transfer accessibility. The sensitivity analysis shows that improving the physical accessibility of transfer nodes is an especially efficient strategy for enhancing equity among mobility-constrained populations. This finding challenges the traditional planning mindset that emphasizes "service quantity," such as adding routes or reducing headways.

For mature multimodal systems, "service quality"—particularly at critical transfer nodes—may generate greater marginal equity benefits than simply increasing service volume. Installing elevators, ramps, or weather-protected corridors can produce larger accessibility gains for elderly passengers, people with disabilities, or parents with strollers than adding an additional bus trip. This suggests that planning should move beyond macro-level route design to also prioritize micro-level node optimization, achieving coordinated improvements across both "lines" and "points."

B. *Comparison with Existing Research*

The conclusions of this study align closely with Dai et al. [17], who found that the difference principle outperforms utilitarianism in promoting equity along a single bus corridor. However, this research extends those findings to a complex, real-world multimodal network that incorporates transfer behavior, thereby enhancing external validity and practical relevance.

Compared with traditional egalitarian models that aim to minimize the Gini coefficient (e.g., Verma et al. [27]), the D-Design approach is more targeted and resource-efficient. The Gini coefficient captures aggregate inequality but does not specify who the disadvantaged are. Minimizing it may lead to broadly dispersing resources across all non-central areas, potentially diluting impact. By contrast, D-Design directs resources explicitly toward a socioeconomically defined least advantaged group, enabling more precise and efficient intervention.

Moreover, this study advances the literature by quantitatively characterizing the equity – efficiency trade-off through a Pareto frontier. While many previous works acknowledge this trade-off qualitatively—or present only a single compromise solution—this research provides a full "decision menu." Policymakers can clearly observe the efficiency costs associated with different equity levels, enabling more transparent and accountable decision-making tailored to varying social priorities and development stages.

C. *Policy Implications*

The findings carry several important implications for urban transport policy:

- From "Efficiency First" to "Equity Compatible": Planning paradigms should move beyond maximizing passenger throughput or minimizing delay alone. Transport equity — particularly safeguarding disadvantaged groups — should become a core, measurable objective in planning and evaluation frameworks.
- Targeted Subsidies and Differentiated Services: Public transport funding should be precisely targeted rather than uniformly distributed. For example, service frequency could be prioritized in low-income or affordable housing areas, and demand-responsive community services could support neighborhoods with high concentrations of elderly or disabled residents.
- Focus on Micro-Renewal of Transfer Nodes: Investments in upgrading existing transfer hubs may yield greater equity returns than large-scale expansion projects. Strategic "micro-surgery" — adding elevators, improving signage, or enhancing sheltered walkways — can offer cost-effective and impactful improvements.
- Establish Equity Monitoring Mechanisms: Authorities should implement regular accessibility monitoring systems, publish periodic reports disaggregated by area and social group, and use these data to guide adaptive policy adjustments.

D. *Theoretical and Practical Value*

Theoretically, this study builds a bridge between abstract ethical philosophy and concrete transport engineering practice. By operationalizing Rawls's difference principle within a computational optimization framework, it demonstrates how normative values can be embedded into infrastructure planning—offering a model for computational social science approaches to value-sensitive design.

Practically, the ethics-aware framework and optimization models developed here can be integrated into urban planning decision-support systems. They provide planners with transparent tools to evaluate equity impacts and generate solutions that balance fairness and efficiency, contributing to more evidence-based and refined urban governance.

E. *Limitations and Future Research*

Despite its contributions, the study has several limitations that point to promising avenues for future work:

- Static Modeling Assumption: The current model assumes stable demand and network conditions. Real-world systems are dynamic. Future research could incorporate time-varying demand and congestion effects into dynamic ethics-aware models.

- Simplified Behavioral Assumptions: Passengers are assumed to choose routes based solely on shortest generalized travel time. More advanced discrete choice models could incorporate preferences for reliability, comfort, or crowding.
- Fixed Definition of Vulnerable Groups: Although multidimensional, the definition of the least advantaged group remains exogenous and static. In reality, vulnerability can be contextual—for instance, passengers with heavy luggage or strollers may face temporary disadvantages. Developing dynamic identification methods would enhance realism.
- Lack of Long-Term Feedback Effects: The model does not account for long-term land use and transport interactions (LUTI). Transport improvements can influence residential and employment patterns over time. Integrating ethics-aware design with LUTI models represents a challenging yet valuable direction for future research.

In summary, this study demonstrates that embedding ethical principles into multimodal network design is not merely a philosophical exercise—it has measurable, policy-relevant consequences. By transforming abstract moral reasoning into operational decision tools, it opens new pathways for advancing both transport equity and responsible urban governance.

VIII. Conclusion

Aiming to promote the coordinated advancement of equity and efficiency in urban transit systems, this study developed and validated an ethics-aware design framework for multimodal accessible transportation. By extending and operationalizing Rawls's difference principle within a real and complex urban network integrating metro, bus, and bike-sharing systems, the research systematically compared design strategies guided by different ethical principles and quantitatively examined the trade-off between equity and efficiency. The main conclusions can be summarized as follows.

First, in realistic urban contexts characterized by uneven distributions of opportunities and resources, the traditional utilitarian design paradigm tends to intensify accessibility inequality. Explicitly incorporating ethical principles — particularly Rawls's difference principle — provides a necessary pathway toward achieving transport equity. Design schemes grounded in the difference principle significantly enhance accessibility for the most disadvantaged groups, thereby narrowing the "mobility divide" across social strata.

Second, transfer links within multimodal systems represent a critical bottleneck shaping transport equity, especially for mobility-constrained populations. Treating the physical accessibility of transfer nodes as an endogenous design variable and prioritizing targeted improvements emerges as a highly cost-effective strategy for promoting equity.

Third, equity gains are not cost-free; they are typically accompanied by some reduction in overall system efficiency. However, this trade-off is neither absolute nor unmanageable. The Pareto frontier constructed in this study offers policymakers a transparent "decision menu," enabling informed and accountable choices that reflect societal values and developmental priorities while clearly understanding the consequences of alternative options.

Fourth, by integrating publicly available and reproducible urban datasets with advanced optimization techniques, the proposed ethics-aware design framework transforms abstract ethical reasoning into a practical, computable planning tool. This methodological integration bridges normative theory and engineering application.

In sum, this study advances theoretical understanding of transport equity while providing an innovative set of optimization tools for multimodal network design. More importantly, it establishes a solid scientific foundation and a feasible technical pathway for urban planners and policymakers seeking to foster a more inclusive, just, and sustainable urban mobility system. Future research should further incorporate dynamic processes, behavioral responses, and long-term land use – transport interactions to strengthen the model's explanatory capacity and policy relevance in real-world contexts.

References

[1] Banister, D., & Schwanen, T. (2019). Sustainable development goals and transport: A review of synergies and tensions. Journal of Transport Geography, 78, 102540. DOI:10.1016/j.jtrangeo.2019.102540

[2] Banister, D., & Schwanen, T. (2019). Sustainable development goals and transport: A review of synergies and tensions. Journal of Transport Geography, 78, 102540. https://doi.org/10.1016/j.jtrangeo.2019.102540

[3] Martens, K. (2017). Transport justice: Designing fair transportation systems. Routledge. https://doi.org/10.4324/9781315110120

[4] Lucas, K. (2012). Transport and social exclusion: Where are we now? Transport Policy, 20, 105 – 113. https://doi.org/10.1016/j.tranpol.2011.07.004

[5] World Health Organization. (2007). Global age-friendly cities: A guide. World Health Organization. https://doi.org/10.15415/who.9789241563200

[6] Golub, A., & Martens, K. (2014). Equity analysis for transportation planning: A review of methods and challenges. Journal of Transport Geography, 41, 158 – 169. https://doi.org/10.1016/j.jtrangeo.2014.06.009

[7] Geurs, K. T., & Van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: Review and research directions. Journal of Transport Geography, 12(2), 127 – 140. https://doi.org/10.1016/j.jtrangeo.2003.09.002

[8] Talebian, A., & Mishan, M. (2018). A multi-objective optimization model for bus transit network design and frequency setting with environmental and social equity considerations. Sustainable Cities and Society, 42, 573–587. https://doi.org/10.1016/j.scs.2018.06.023

[9] Verma, A., Singh, S. K., & Mishra, N. (2019). A multi-objective genetic algorithm-based approach for transit network design with equity-based objectives. Public Transport, 11(3), 547 – 584. https://doi.org/10.1007/s12469-019-00224-0

[10] Rawls, J. (1999). A theory of justice (Rev. ed.). Harvard University Press. https://doi.org/10.4159/9780674042253

[11] Van Wee, B., & Geurs, K. T. (2011). A critical review of the literature on the social impacts of transport. Transport Policy, 18(5), 649–661. https://doi.org/10.1016/j.tranpol.2011.01.005

[12] Dong, X., Ben-Akiva, M. E., & Bowman, J. L. (2006). A unified framework for accessibility and travel behavior modeling. Transportation Research Part A: Policy and Practice, 40(2), 114–133. https://doi.org/10.1016/j.tra.2005.07.004

[13] Van Goeverden, C. D., & Van Wee, B. (2019). Ethical theories and their application to transport. Transport Reviews, 39(1), 4 – 21. https://doi.org/10.1080/01441647.2018.1525305

[14] Lucas, K., Van Wee, B., & Maat, K. (2016). A review of the literature on the social impacts of transport. Journal of Transport & Health, 3(2), 262–275. https://doi.org/10.1016/j.jth.2016.02.005

[15] Camporeale, R., Caggiani, L., & Ottomanelli, M. (2019). A multi-objective approach for designing equitable and efficient transit route networks. Transportation Research Part B: Methodological, 123, 115–136. https://doi.org/10.1016/j.trb.2019.02.004

[16] Pereira, R. H., Schwanen, T., & Banister, D. (2017). Distributive justice and equity in transportation. Transport Reviews, 37(2), 170–191. https://doi.org/10.1080/01441647.2016.1230308

[17] Martens, K., Golub, A., & Robinson, G. (2012). A justice-theoretic approach to the distribution of transportation benefits: Implications for transportation planning practice in the United States. Transportation Research Part A: Policy and Practice, 46(4), 684–695. https://doi.org/10.1016/j.tra.2011.11.005

[18] Dai, T., Li, J., & Nie, Y. M. (2023). Accessibility-based ethics-aware transit design. Transportation Research Part B: Methodological, 176, 102816. https://doi.org/10.1016/j.trb.2023.102816

[19] Kepaptsoglou, K., & Karlaftis, M. G. (2009). Transit route network design problem: A review. Transport Reviews, 29(2), 255 – 277. https://doi.org/10.1080/01441640802445573

[20] Farahani, R. Z., Miandoabchi, E., Szeto, W. Y., & Rashidi, H. (2013). A review of urban transportation network design problems. European Journal of Operational Research, 229(2), 281 – 302. https://doi.org/10.1016/j.ejor.2013.03.005

[21] Guihaire, V., & Hao, J. K. (2008). Transit network design and scheduling: A global review. Transportation Research Part A: Policy and Practice, 42(10), 1251 – 1273. https://doi.org/10.1016/j.tra.2008.04.009

[22] Hansen, W. G. (1959). How accessibility shapes land use. Journal of the American Institute of Planners, 25(2), 73 – 76. https://doi.org/10.1080/01944365908977275

[23] Cervero, R., Rood, T., & Appleyard, B. (1999). Tracking accessibility: Employment and housing opportunities in the San Francisco Bay Area. Environment and Planning A, 31(7), 1259 – 1278. https://doi.org/10.1068/a311259

[24] Iacono, M., Krizek, K. J., & El-Geneidy, A. (2010). Measuring non-motorized accessibility: Issues, data, and methods. Transport Reviews, 30(4), 433–455. https://doi.org/10.1080/01441647.2010.494212

[25] Nassir, N., Hickman, M., & Ma, Z. L. (2016). A utility-based travel impedance measure for public transit network accessibility. Transportation Research Part A: Policy and Practice, 88, 26 – 39. https://doi.org/10.1016/j.tra.2016.03.005

[26] Fan, W., & Machemehl, R. B. (2006). A multi-objective optimization model for the transit network design problem. Transportation Research Part A: Policy and Practice, 40(8), 617 – 638. https://doi.org/10.1016/j.tra.2005.12.005

[27] Daskin, M. S., Snyder, L. V., & Berger, R. T. (2005). Facility location in supply chain design. In C. R. Sox, & M. S. Daskin (Eds.), Logistics systems: Design and optimization (pp. 39 – 65). Springer US. https://doi.org/10.1007/0-387-23159-8_3

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to colleagues and experts who provided constructive feedback on the research design and interpretation of findings. We also acknowledge the assistance received in data organization and manuscript preparation.

FUNDING

None.

AVAILABILITY OF DATA

Not applicable.

AUTHOR CONTRIBUTIONS

Jiayi Chen: Conceptualization; Methodology; Formal analysis; Software; Data curation; Visualization; Writing – original draft; Writing – review & editing.

Shuyi Zhang: Conceptualization; Validation; Investigation; Resources; Supervision; Writing – review & editing.

COMPETING INTERESTS

The authors declare no competing interests.

Publisher's note WEDO remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.