Operationalizing Social Justice Theories in Transport Resource Allocation

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Short summary

Equity in transport planning is increasingly recognized as vital to addressing disparities in resource allocation and accessibility. This study bridges theoretical social justice principles with operational decision-making by integrating four commonly discussed distributive justice theories—Utilitarianism, Rawls' Egalitarianism, Prioritarianism, and Capabilitarian Sufficiency—into a bilevel bus frequency optimization model. The study introduces equity-oriented formulations to reflect the distinct distributive principles of the justice theories, and propose justice theory-driven equity metrics to evaluate the resultant distributive impacts. Using cumulative opportunity as an accessibility measure, the different equity frameworks are applied to Canberra's southern suburbs. Results highlight how different justice principles yield distinct policy outcomes, emphasizing the need to align equity frameworks with specific objectives and societal goals. This research provides policymakers with a comparative framework to assess trade-offs not only between equity and efficiency but also across distributive principles, advancing justice-oriented decision-making in transport resource allocation.
Keywords: Social justice theory, transport equity, frequency optimization, resource allocation

1 Introduction

Social equity refers to how benefits and costs are distributed and to what extent that distribution is deemed fair or appropriate (Litman, 2022). There is growing research exploring the application of various social justice theories to guide decisions in infrastructure planning (Vecchio & Martens, 2021; Martens et al., 2014; Golub & Martens, 2014; Martens et al., 2012), focusing on the social equity impacts of resource allocation decisions.

Lewis et al. (2021) provided an extensive review of different justice theories from the fields of sociology, psychology, philosophy and economics, and provide a summary of theories considered explicitly and implicitly in transportation literature. The review shows that Utilitarian-ism, Rawl's Theory of Justice, the Capabilities Approach and Prioritarianism have received the most attention in the transport literature, although the definitions presented within the transportation literature sometimes differ from the philosophical definitions. Utilitarianism focuses on maximizing the overall happiness or well-being (utility), which is often summarized as "the greatest happiness for the greatest number" (Mill, 1895). The existing utilitarian approach to transport planning has been widely criticized in the literature for its focus on aggregated welfare and neglect of individual needs (Vecchio & Martens, 2021; Martens et al., 2014; Van Wee & Roeser, 2013; Schiefelbusch, 2010). Under the utilitarian planning context, all individuals are given equal weight in the calculation of aggregate social welfare, with the objective to maximize whatever social outcome that is deemed most important at that moment in time (Binmore, 1998). Rawls' Theory of Justice (Rawls, 1971), or Rawls' Egalitarianism, emphasizes two principles: equal rights and freedoms for all (greatest equal liberty) and the difference principle, which accepts inequalities only if they benefit the least-advantaged. Unlike traditional Egalitarianism, which promotes absolute equality, Rawls' approach focuses on equitable resource distribution to reduce disparities. While widely cited in transport literature, many studies focus on the difference principle rather than the broader egalitarian perspective of the theory (Lewis et al., 2021).If utilitarianism assigns equal weight to everyone, and Rawls' Theory of justice assigns infinite weight to the interest of the least-advantaged individual

(Harsanyi, 1975), then prioritarianism appears to be a middle ground. Prioritarianism is based on the view that benefits become more significant when they are received by someone who is worse off (Arneson, 2000). The theory argues that the moral value of a benefit, or the negative impact of a burden, decreases as the recipient's well-being improves (Casal, 2007). In other words, prioritarianism assigns different weights to benefits received by different individuals, depending on their position in the distributive spectrum (Martens et al., 2014). The Capabilities Approach (CA), developed by Amartya Sen and furthered by Martha Nussbaum (Sen, 1995; Amartya & Amartya, 2009; Nussbaum & Sen, 1993; Nussbaum, 2011), is primarily concerned with promoting basic capability equality and defends the establishment of minimum levels of basic capabilities (Nussbaum, 2011; Clark, 2005), which relates to the notion of "Sufficientarianism" (Cooper & Vanoutrive, 2022; Luz & Portugal, 2022; Adli & Chowdhury, 2021; Nahmias-Biran & Shiftan, 2020; Nielsen & Axelsen, 2017). Resources are the means to achieve valued outcomes, but their conversion into capabilities or freedoms to achieve what one values depends on personal, social, and environmental factors (Sen, 1995; Amartya & Amartya, 2009). Capabilitarian sufficiency (Axelsen & Nielsen, 2015; Nielsen & Axelsen, 2017) combines the CA and sufficiency principles to address concerns about the arbitrariness or one-dimensionality of the 'sufficiency threshold' with capabilitarian insights.

This study aims to contribute to the operationalization of social justice theories in transport resource allocation and explores the tradeoff between different justice principles. Building on existing literature, this paper presents formulations of how different theories of justice may be integrated into a bus frequency optimization problem i.e., an example of a transport resource allocation problem. Different justice theory-driven equity metrics are also proposed to assess the resultant equity impacts through the lens of different distributive principles. This comparative analysis framework hopes to demonstrate the practical implications of adopting various justice principles in transport planning, allowing for a nuanced understanding of how different social justice theories may inform transport resource allocation.

2 Methodology

In this study, we first develop a bilevel formulation which builds on the non-linear frequency optimization model proposed by Constantin & Florian (1995), where the leader problem determines the allocation strategy, and the follower problem is a transit assignment model which emulates users' desire to minimize their expected travel time. The existing frequency optimization model and the reformulation provide a strong mathematical structure to integrate fairness metrics and enable discussions of model realism. We adopt the discretized frequency approach proposed by Martínez et al. (2014) to linearize the model.

Consider a directed graph $G = (N, A)$. The set of nodes N represents either bus stops N_p, endpoints of street segments N_s, or zone centroids. The set of arcs A includes the travel arcs (in-vehicle) A_T, boarding arcs A_B, alighting arcs A_A, and walking arcs between stop nodes and centroids. For simplicity, it is assumed that demand is generated at the bus stop i.e., no walking arcs between stop nodes and centroids. A_N^+ and A_N^- represent the set of outgoing and incoming arcs of node n respectively. L represents the set of lines, θ represents the set of discretized domain of frequency. Each element θ_f is a nonnegative value representing a possible value for the frequency of any line. Each line passing a given stop has one boarding arc for each value of θ. Constantin & Florian (1995) and Martínez et al. (2014) provide detailed explanation of the existing frequency optimization model and its properties. Let $\mathbf{u}$ be the vector of travel time experienced by each Origin-Destination (OD) pair $k \in K$. Let $o(k)$ and $d(k)$ be the origin and destination nodes of OD $k \in K$ respectively. Let $\psi_k \in \{0, 1\}$ be a binary variable which determines if the user travel time of OD k in within λ minutes at planning period t, i.e., $\psi_k = 1$ if $\frac{u_k}{\sigma_k} \leq \lambda$, and $\psi_k = 0$ if $\frac{u_k}{\sigma_k} \geq \lambda$. Then, let ι_n be the number of opportunities present at node $n \in N_p$, such that the total number of opportunities that can be reached from node n (η_n) is given by Eq. (1):

$$\eta_n = \sum_{k \in K: o(k)=n} \iota_{d(k)} \psi_k + \iota_n \forall n \in N_p \tag{1}$$

The total number of accessible opportunities is the sum of existing opportunities at the node and all opportunities at nodes that can be reached within the given time threshold. In this case, the set of ODs represent all the feasible trajectories between nodes.

A big-M constraint is introduced to enforce the binary decision variable, as shown in Eq. (2), where M represents a sufficiently large number.

$$\frac{u_k^t}{\sigma_k^t} - \lambda \leq M(1 - \psi_k^t) \tag{2}$$

Let x_l be a variable representing the number of buses allocated to line l, y_{lf} is a binary decision variable which determines if a frequency θ_f is selected for line l. B_{fleet} represents the existing resource budget, u_k is the travel time for OD pair k. σ_k is the demand of OD pair k and b_{nk} is the net inflow or outflow at a node n for OD pair k. We denote $TAP(\mathbf{y})$ as the set of optimal solutions of the lower level Transit Assignment Problem (TAP). The general bilevel frequency optimization model for a given equity-oriented objective $Z(\boldsymbol{\eta})$ is summarized in Eq. (3).

$$
\begin{aligned}
\min_{x,y,u,v,w,\eta,\psi} \quad & Z(\boldsymbol{\eta}) && && \text{(3a)}\\
\text{s.t.} \quad & x_l = \sum_{f\in F} \theta_f y_{lf} \sum_{a\in l} c_a && \forall l \in L && \text{(3b)}\\
& \sum_{l\in L} x_l \leq B_{fleet} && && \text{(3c)}\\
& \eta_n = \sum_{k\in K:o(k)=n} \iota_{d(k)}\psi_k + \iota_n && \forall n \in N_p && \text{(3d)}\\
& \frac{u_k^t}{\sigma_k^t} - \lambda \leq M(1-\psi_k^t) && \forall k \in K && \text{(3e)}\\
& \sum_{f\in F} y_{lf} = 1 && \forall l \in L && \text{(3f)}\\
& u_k = \sum_{a\in A} c_a v_{ak} + \sum_{n\in N_p} w_{nk} && \forall k \in K && \text{(3g)}\\
& \sum_{a\in A_n^+} v_{ak} - \sum_{a\in A_n^-} v_{ak} = b_{nk} && \forall n \in N, k \in K && \text{(3h)}\\
& v_{ak} \leq \theta_{f(a)} w_{nk} && \forall n \in N, a \in A_n^+, k \in K && \text{(3i)}\\
& v_{ak} \leq \sigma_k y_{l(a)f(a)} && a \in A_B, k \in K && \text{(3j)}\\
& y_{lf} \in \{0,1\} && \forall l \in L, f \in F && \text{(3k)}\\
& \psi_k \in \{0,1\} && \forall k \in K && \text{(3l)}\\
& \eta_n \geq 0 && \forall n \in N_p && \text{(3m)}\\
& \mathbf{u} \in TAP(\mathbf{y}) && && \text{(3n)}
\end{aligned}
$$

Eq.(3b) and Eq.(3c) ensure the frequency allocation does not exceed the resource budget. Eq.(3d) and Eq. (3e) are cumulative opportunities constraints articulated in Eq.(1) and Eq.(2). Eq.(3f) ensures only one frequency is selected for each transit line, Eq.(3g) formulates OD travel time u_k in terms of OD-specific link flow v_{ak} and waiting time at node w_{nk}. Eq.(3h) ensures flow conservation at each node. Eq.(3i) represents the frequency share rule which distribuites demand corresponding to a given OD pair among different lines. Eq.(3j) only permits flow on arcs that have the optimal frequency, and the flow must be less than the given demand for each OD.

Formulating equity

Utilitarianism (UT)

The UT framework would aim to maximize the total accessibility across all non-transit nodes $n \in N_p$. Let κ_n be the population at node n, the objective function may be formulated as:

$$\max \sum_{n\in N_p} \eta_n \kappa_n \tag{4}$$

It is noted that η_n is not an aggregated measure, but indicates a level of accessibility for a given node n, therefore the population at each node is multiplied by their respective accessibility level to obtain the total accessibility level for the system.

The UT metric is then defined as the average accessibility level per person:

$$\frac{\sum_{n\in N_p}\eta_n\kappa_n}{\sum_{n\in N_p}\kappa_n} \tag{5}$$

Prioritarianism (PR)

The Prioritarian framework favours more disadvantaged nodes by appending node-specific weight (ρ_n) in the objective function, which reduces the efficiency focus and strives for a more equitable distribution of accessibility across nodes:

$$\max \sum_{n\in N_p} \rho_n\eta_n\kappa_n \tag{6}$$

Similarly, a potential PR metric is the average accessibility of the $\mu\%$ population with lowest accessibility to opportunities. Let $Q = \{\overline{q_1}, \overline{q_2}, ..., \overline{q_{|Q|}}\}$ be the set of accessibility levels for the entire population and $\overline{q_i}$ is the accessibility of person i, sort accessibility travel time in ascending order such that $\overline{q_1} \geq \overline{q_2} \geq \overline{q_{|Q|}}$. For a population size of $|Q|$ and that $|Q| = \sum_{n\in N_p}\kappa_n$, the population with low accessibility is given by $m = |Q| \times \mu\%$. The metric is formulated as:

$$\frac{1}{m}\sum_{i=1}^{m}\overline{q_i} \tag{7}$$

Capabilitarian Sufficiency (CS)

Within the CS framework, the number of opportunities that can be reached by an individual can be considered *resources*. These resources are crucial because they provide basis upon which individuals can convert these means to actual *capabilities*, which enable the freedom or ability to achieve certain *functionings*. The actual capabilities in this context may be the ability to secure a job, which depends not only on the availability of jobs but also on the other factors such as personal skills, professional experience, individual circumstance etc. As such, let $C_n(\eta_n)$ be a node-specific function that converts accessible jobs to securable jobs. For simplicity, it is assumed that each node n only has one user class. The CS objective function may be formulated as:

$$\max \sum_{n\in N_p} C_n(\eta_n) \tag{8}$$

It is noted that neither the CA nor the Sufficientarian principles specify the capability-maximizing objective. The CA is an evaluative framework and Sufficientarianism imposes a bound rather than an objective. In this case, a capability-maximizing-objective reflects the planning goal of greatest possible enhancement of individuals' capabilities within the given constraints. Its additive nature may mirror as-pects of the Utilitarian distributive pattern, but it differs fundamentally by focusing not on maximizing utility but on expanding the individual liberties.

Let β be in the pre-defined capability threshold. The sufficient level of accessibility is ensured by imposing a constraint:

$$C_n(\eta_n) \geq \beta \qquad \forall n \in N_p \tag{9}$$

Let $[C_k(u_k/\sigma_k) \geq \beta]$ be an indicator function where $[C_k(u_k/\sigma_k) \geq \beta] = 1$ if the condition is true, and 0 otherwise. A Capabilitarian Sufficient metric may be formulated as the percentage of population below a given capability threshold or above a given negative capability threshold:

$$\frac{\sum_{n\in N_p}[C_k(u_k/\sigma_k) \geq \beta]}{\sum_{n\in N_p}\kappa_n} \tag{10}$$

Rawls' Egalitarianism (RE)

The RE framework aims to maximize average accessibility for the most-disadvantaged individual i.e., the most disadvantaged node:

$$\max \min_{n \in N_p} \eta_n \tag{11}$$

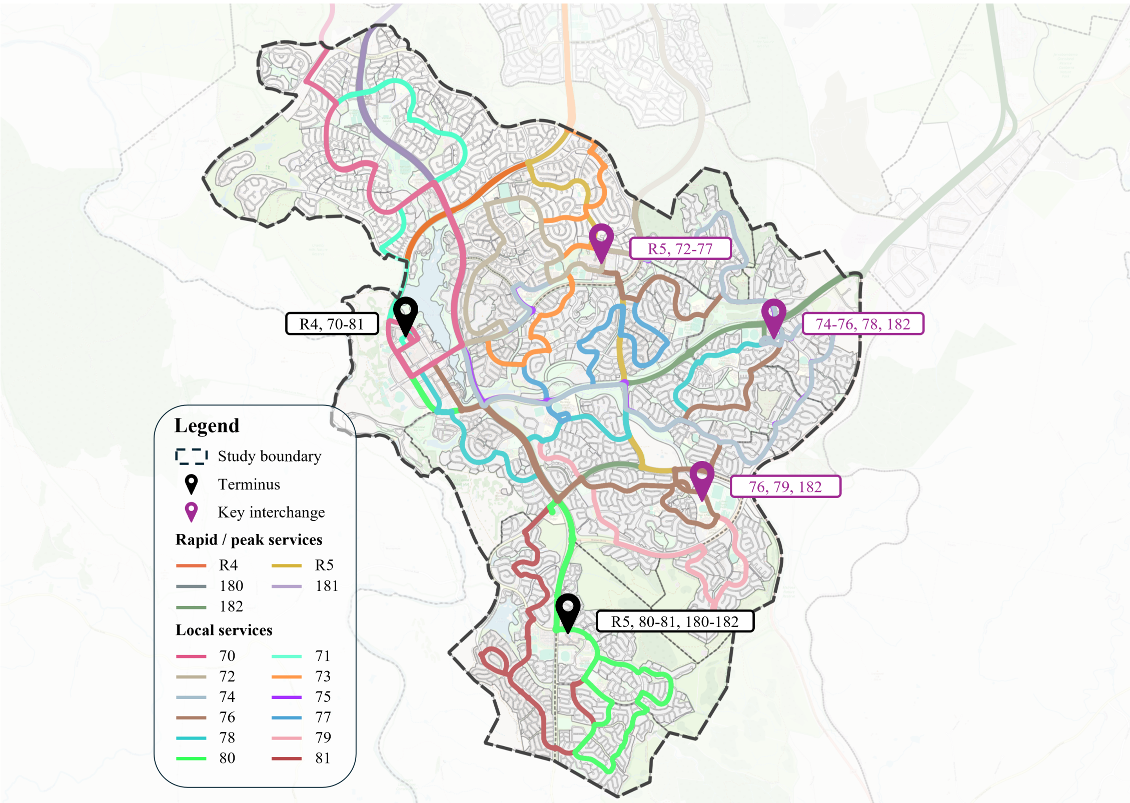
A key prerequisite to *Rawls' difference principle* is that roles and opportunities should be open to all under conditions of fair equality of opportunity. In alignment with this principle, the proposed formulation assumes all opportunities are open to the population i.e., no opportunity-specific parameters are introduced that would privilege certain individuals in terms of accessibility to opportunities.

The RE metric is then the average accessibility of the most-disadvantaged user class (node):

$$\min_{n \in N_p} \eta_n \tag{12}$$

3 Application to the South Canberra Network

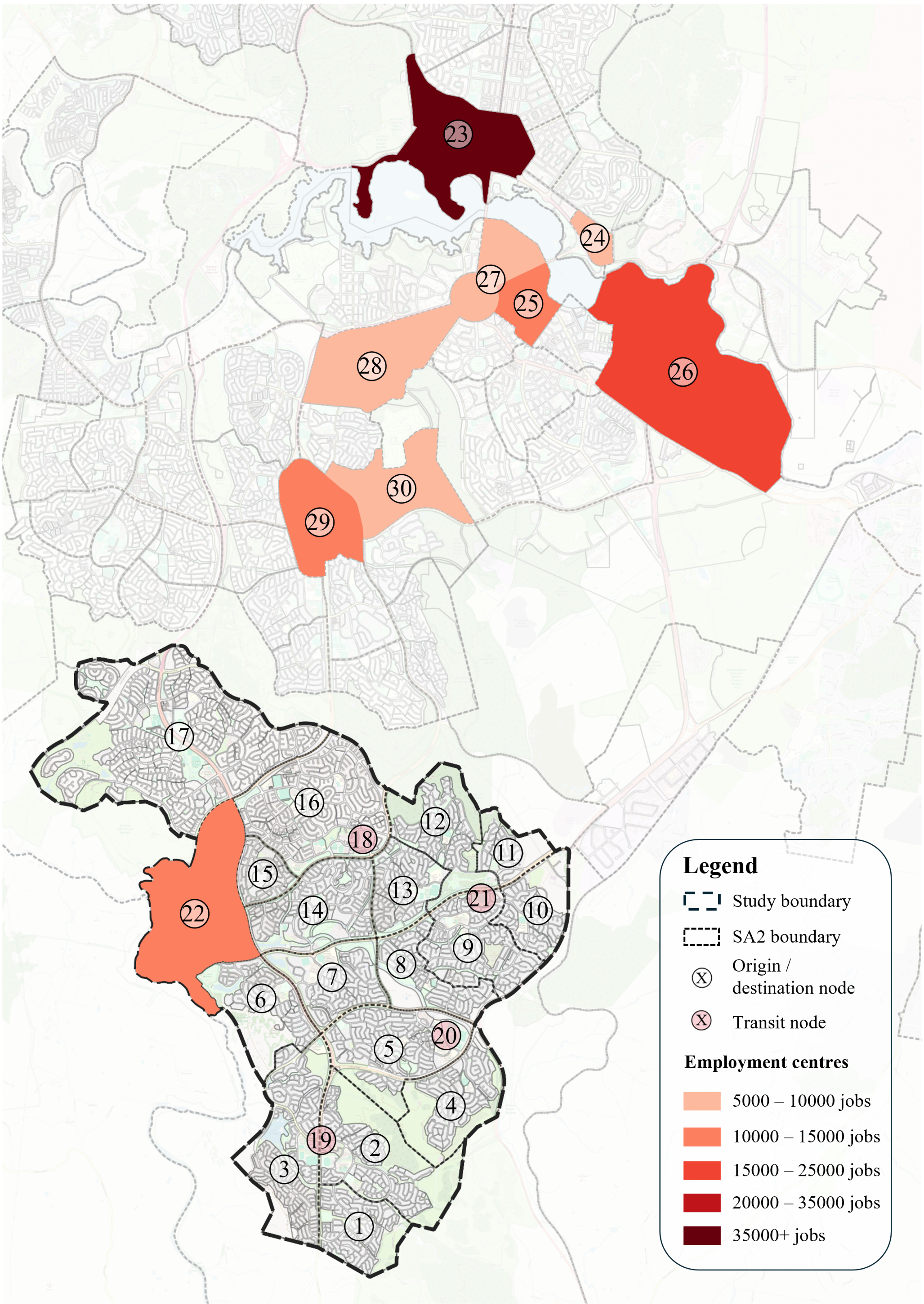
The southern suburbs of Canberra are mostly low-density residential areas and natural landscapes, with a number of local centers providing commercial amenities and services. These local centers also serve as key bus interchanges. The existing transit network within the study area is shown in **Figure 1**. The transit network within the study area has 2 rapid routes, 3 peak hour routes and 12 local routes. Most properties are within 400m of a bus stop, serviced by a local route that provides connection to key interchanges within the suburbs or beyond the suburbs.The network consists of 30 nodes, 49 undirected edges and 3 directed edges. Travel time between nodes on different bus routes are estimated using the ACT General Transit Feed Specification.



Map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org

Figure 1: South Canberra bus network

Statistical Area Level 2 (SA2) is a critical geographical unit used to analyzse and present data in Australia. This analysis focuses on the number of jobs accessible from each SA2 area in the South Canberra area within a travel time threshold of $\beta = 75$ minutes. The set of OD pairs captures the trajectories from all SA2 areas in South Canberra to the key employment centers. **Figure 2** shows the location of these key employment centers in Canberra offering more than 5000 jobs.



Map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org

Figure 2: Key employment centers in Canberra offering more than 5000 jobs

For the PR framework, two sets of ρ_n values determined by different dimensions of equity are applied to assess the appropriateness of parameter selection. The first set of ρ_n^a values are determined by the base case (utilitarian) job accessibility. The PR metric is defined as the average job accessibility of the 20% population with the lowest job accessibility. The second set of ρ_n^e values are determined by the existing unemployment rates of the SA2 areas. The purpose of this scenario is to understand the appropriateness of assessing project merit using a PR metric that considers a different dimension than the prioritization criteria.

For the CS framework, a node-based conversion factor π_n is proposed to represent the ability of an individual (from node n) to convert the jobs they can access, to jobs that can secure. Given the lack of specific case studies on the personal, environmental, and social attributes affecting people's abilities and choices in realizing employment opportunities in the study area, the Socio-Economic Indexes for Areas (SEIFA) published by the Australian Bureau of Statistics is used as proxy conversion factors. The objective of the CS framework is given by $\max \sum_{n \in N} \pi_n \eta_n$. Incorporating the capabilitarian insight, this study adopts an 'effective job accessibility' threshold, which is obtained by applying the conversion factors i.e., the weighted composite indexes to the number of physically accessible jobs. The sufficiency constraint can be formulated as $\pi_n \eta_n \geq \beta \quad \forall n \in N$.This study adopts the value of $\beta = 21000$, which is approximately 25% improvement from the minimum effective job accessibility under the UT framework.

Lastly, in addition to the four justice theory frequency optimization frameworks, the Gini Index is used to measure the distributive patterns from an Egalitarian lens. Assessing end outcomes from an egalitarian lens adds an important dimension to equity assessment, allowing us to evaluate how effectively different frameworks aimed at improving equality of opportunity (except for Utilitarianism) succeed in achieving equality of outcomes.

Results and discussion

Table 1 summarizes the job accessibility for each node under each justice theory-driven bus frequency optimization framework. Below each column of node accessibility, the respective UT metric, RE metric, CA metric, PR metric, Gini coefficient, and model objective value are provided. Each justice theory framework demonstrates distinct distributive patterns, yielding varied equity outcomes. When evaluated against the UT metric, the UT framework excels due to its efficiency-driven objective, while the RE framework, which disregards efficiency, performs the poorest. The PR framework balances efficiency and equity, achieving slightly lower efficiency than UT but prioritizing disadvantaged groups. However, it struggles to improve node 15's accessibility significantly under the efficiency-driven undertone of its approach. In contrast, the RE framework assigns infinite weights to the most disadvantaged, achieving higher minimum accessibility than other frameworks. The CS framework strikes a compromise, lowering accessibility disparity more effectively than UT or PR by reallocating resources to mitigate equity violations, though its sufficientarian pattern limits further improvements once minimum thresholds are met.

The unemployment-based PR framework underperforms in equity measures due to its indirect relationship between prioritization criteria and equity indicators, highlighting the limitations of its approach. The CS framework outperforms the PR framework in accessibility disparity (Gini coefficient) due to its focus on effective accessibility thresholds. However, frameworks like CS and unemployment-based PR often address socio-economic criteria rather than existing accessibility conditions, leading to mixed equity outcomes when compared to frameworks explicitly targeting the most disadvantaged.

Under the PR metric, the PR framework surpasses RE, balancing benefits and disbenefits across the population, while RE focuses exclusively on the most vulnerable, often at the expense of others. All justice frameworks reduce accessibility disparity better than UT, with the unemployment-based PR achieving the lowest Gini coefficient, though this focus on a single equity measure risks overlooking broader distributive impacts. Ultimately, no single framework demonstrates overall superiority, as distributive impacts depend on network context, data, and modeling approach. A comparative analysis offers critical insights into the strengths and limitations of justice frameworks under various conditions, emphasizing their tailored applicability to specific contexts.

Table 1: Comparison of job accessibility distribution under each justice theory framework

Node	Population	UT	RE	PR ρ_n^a	PR ρ_n^e	CS
1	3100	125857	125857	125857	125857	125857
2	2967	126604	126604	126604	126604	126604
3	4476	118641	87908	87908	118641	87908
4	2284	88757	88757	88757	88757	88757
5	3288	119592	119592	119592	119592	119592
6	2140	88810	41483	88810	88810	88810
7	2357	88965	88965	119135	88965	88965
8	1675	118920	88750	118920	41423	118920
9	2873	126266	119312	126266	119312	119312
10	1497	119003	41506	57503	26653	104830
11	763	118803	118803	118803	118803	125757
12	1652	102994	57491	102994	34203	118991
13	1656	34254	88872	88872	34254	34254
14	2784	89091	89091	103264	89091	89091
15	883	34031	41322	34031	34031	41322
16	4102	134197	134197	134197	134197	134197
17	8011	104486	104486	104486	133804	104486
22	2524	132051	132051	132051	132051	69988
UT metric		109092	100860	108509	105690	103030
RE metric		34031	41322	34031	26653	34254
CS metric		1.8%	3.1%	8.3%	1.8%	0
PR metric		66963	45451	67050	43220	58368
Gini coefficient		0.130	0.095	0.119	0.060	0.114

4 Conclusions

The findings of this study have significant implications for transport planning and broader policy-making, particularly in how equity goals are defined and measured at different planning levels. For example, a transit planner may view accessibility as a goal and therefore adopt the RE framework to provide targeted support for the populations with the least accessibility. On the other hand, a policymaker may see accessibility as a means to improve employment rates and prioritize areas with existing employment challenges. While both attempts to distribute accessibility, the scopes can vary vastly. The comparative analysis presented in this study provides a basis for multi-dimensional equity analysis to understand the potential benefit and impact of the strategy from the lens of different justice principles. From the project inception phase, planner could ap-ply different unit and scope to compare the distributive patterns of each shape and establish relevant targets that reflect the preferred distribution. During project development phase, the multi-dimensional analysis pro-vides a quantitative comparison across different strategies using different justice theory-based metrics to inform the equity impacts analysis in the project appraisal process. Ultimately, the proposed equity-oriented bus frequency optimization framework and the comparative analysis against different metrics offer a valuable tool for decision-makers aiming to create more equitable transit systems. However, the choice of equity framework and the associated parameters must be carefully consid-ered to reflect broader social goals.

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