sustainability

MDPI

Article

Towards Fair Roads–Manifesto for Fair Traffic Engineering

Kevin Riehl *, Anastasios Kouvelas and Michail A. Makridis

Traffic Engineering Group, Institute for Transport Planning and Systems, 8093 Zürich, Switzerland; kouvelas@ethz.ch (A.K.); mmakridis@ethz.ch (M.A.M.)
* Correspondence: kriehl@ethz.ch

Abstract

Traffic engineering aims to control infrastructure and population behaviour to achieve optimal usage of road networks. Fairness is fundamental to stimulate cooperation in large populations, and plays an important role in traffic engineering, as it increases the well-being of users, improves driving safety by rule adherence, and overcomes public resistance at legislative implementation. Despite the importance of fairness, only a few works have translated fairness into the transportation domain, with a focus on transportation planning rather than traffic engineering. Moreover, existing works in traffic engineering discuss fairness superficially and insufficiently, focussing on only a few definitions. The mission of this work is (i) to challenge narrowly specified, efficiency-oriented engineering formulations in traffic engineering, (ii) to establish a link to modern fairness theories, and (iii) to highlight the importance of fairness when allocating scarce, public good, mobility resources between road users. To achieve this, a mode-agnostic, distributive fairness framework for mobility resource allocation is proposed. It serves when designing traffic engineering solutions, and convinces in public debates with a useful, argumentative tool-set to confront equity considerations. Ultimately, this enables systematic research and design of fairness-informed control systems, demonstrated by three case studies on signalized intersection management and static road pricing.

Keywords: fairness; traffic engineering; resource allocation; road pricing; signalized intersection management

1. Introduction

The usage of transportation infrastructure is vital for a meaningful, joyful, fulfilling, and dignified life in today's society, as it enables access to the job market, educational & recreational activities, social participation, and marketplaces [1]. For most people, road transportation is the only accessible and affordable means of transportation, as car-dependent societies manifested in most economically flourishing regions world-wide [2]. Access to the road infrastructure is shared by many users, and the utility of the infrastructure depends on its usage; when being used over capacity, congestion arises and the utility diminishes. The ever-growing population, demand for mobility, and over-consumption of shared transportation infrastructure are growing issues in megacities worldwide, leading to conflicts between the users (congestion) [3].

Two general strategies can be distinguished for resolving these conflicts: transportation planning and traffic engineering. Transportation planning is concerned with designing future infrastructure to meet growing demand patterns, while traffic engineering is concerned with sensing, actuating & controlling the existing infrastructure as efficiently as

Academic Editors: Yitong Shang, Xueqian Fu and Qiang Xing

Received: 14 June 2026
Revised: 29 June 2026
Accepted: 6 July 2026
Published: 10 July 2026

possible. Increasing the supply by building more infrastructure can only offer a temporary solution, as it triggers yet another increase in demand in the long run. Therefore, traffic engineering must find better ways to resolve the conflicts arising from existing, capacity-limited road infrastructure [4]. Contrary to transportation planning, traffic engineering must react to given situations in real time, make autonomous decisions, and affect users in the short-term rather than the long-term. The aim of traffic engineering is the management of road transportation systems in order to achieve congestion-free, efficient traffic, optimal utilization of infrastructure (at capacity), and conflict management. Infrastructural control (traffic operations with traffic lights) aims to manage traffic in a way to avoid or mitigate congestion. Behavioural control (e.g., demand management with pricing) affects the behaviour and decision-making process of users using economic instruments, and aims to keep usage at sustainable levels reflecting infrastructural capacity limitations.

Traffic engineering is challenging, as it requires the alignment of conflicting system and user goals. The introduction of traffic engineering solutions can only be achieved through policy-making, which requires public acceptance. One of the major concerns when debating the introduction of solutions is equity considerations and social feasibility [5], where equity considerations usually outweigh potential efficiency improvements in the public discourse [6]. Even though ramp metering [7,8], perimeter control [9], and congestion pricing [10] provide many potential benefits for society, they have been heavily criticised in controversial public debates, which hindered their widespread use in many cases [11].

In recent decades, the vast majority of intellectual energy, societal debates, and public resources have been dedicated to solving congestion and improving transportation efficiency purely from a system perspective [12,13]. Generally, higher efficiency is beneficial, as it reduces congestion and improves the average passenger's travel time. However, this efficiency-driven perspective will not only generate beneficiaries amongst the users. A sole focus on narrowly specified, local efficiency optima can be highly problematic, as misspecified designs of traffic engineering solutions harbour the threat of creating systematic inequalities between the users, unacceptably long waiting times, or excessive queue forming when being applied with limited, local focus. Additionally, transportation efficiency is a multidimensional concept, and optimizing for one goal (e.g., reducing delays) can deteriorate conflicting goals (e.g., more pollution, more energy consumption). As the transportation justice movement states, transportation inequalities affect access to job opportunities, education, and other social activities and, thus, reinforce inequality patterns over the course of time [14,15].

The significance and importance of fairness were largely overlooked by scholars and practitioners alike in the context of traffic engineering solutions, even though fairness heavily determines their success. Solutions that are perceived as fair, are more likely to be approved by political processes, and adopted by the population [6,11]. Fairness is crucial for safety; without the consideration of fairness, users that perceive unfairness (e.g., very long waiting times at traffic lights) are observed to disrespect rules and structures, and to circumvent systems, leading to security incidents [16–19]. Fairness is fundamental to stimulate cooperation in populations with many individuals, and to generate acceptance for social structures and rule-adherence behaviour [20]. Perceived fairness affects the psychological and physical well-being of users as a hygiene factor [20,21].

Even though fairness has been extensively examined in other societal-relevant disciplines such as public healthcare, housing, environmental and social sustainability, only few works have translated fairness into the transportation domain, and most of those focus on transportation planning rather than traffic engineering [22]. Most transportation planning works related to fairness discuss a trade-off between car and transit or active modes of transportation (cycling, walking), exploring and advocating visionary designs for cities that are far away from the life reality of car-dependent societies nowadays [23,24]. The few studies in traffic engineering are limited by the unsystematic study of fairness, by the attachment to specific ideologies of fairness (namely, egalitarianism), by the employment of over-simplifying measures, by the lack of connection with the fairness literature, and by a focus on the vehicles/drivers only [8,9,16,25–36].

Therefore, the mission of this work is threefold. First, this work represents a manifesto to advocate a new paradigm for traffic engineering based on fairness in order to challenge narrowly specified efficiency-only formulations. Second, it is the aim of this work to establish a link between modern fairness literature and algorithmic control in order to empower systematic research on fairness in the domain of traffic engineering. Third, this work aspires to shift the focus on transportation-related equity discussions away from visionary redesigns of roads at the cost of individual motorized transportation towards urgently needed, integrative equity discussions between all individual road users in order to overcome the impediments for traffic demand management strategies and to achieve immediate real-world impact.

We propose a quantitative, ideology-free, distributive, mode-agnostic, and pragmatic fairness framework that shall be useful when designing, discussing, and implementing infrastructural and behavioural control systems, which execute automated decision-making in the context of cybernetic societies [37]. The framework models traffic engineering solutions as resource allocation mechanisms, and identifies delays, pollution, financial costs, and budgets as fairness-relevant, mobility resources [38] in the spirit of modern fairness theories like Rawls [39], Walzer [40] and the capabilities approach [41,42]. Following the Nicomachean transactional view [43], we discuss distributive fairness in a quantitative way, and propose fairness measures for diorthotic fairness (welfare functions), and dianemetic fairness (concentration & dispersion metrics). Moreover, the fairness framework shall equip readers and traffic engineers with an argumentative, convincing toolkit to confront equity concerns in the public discourse.

Three case studies demonstrate usefulness, applicability and feasibility of the framework. The case studies help to understand how fairness and efficiency can be balanced, to showcase a systematic equity discussion, to explore the inherent goal-conflict between efficiency and fairness, and to incorporate the perspective of all modes of transportation. The results reveal, that traffic control improves fairness levels overall, and that fairness and efficiency do not always have to exclude each other. Moreover, the results call attention to leverage more differentiated, systematic discussion from multiple definitions of fairness, rather than to follow single definitions of fairness only. Code and data for reproducing the case studies is provided on GitHub https://github.com/DerKevinRiehl/fair_roads (accessed on 1 July 2026).

The remainder of this work is as follows. Section 2 reviews the literature on fairness, fairness in transportation, in general, and fairness in traffic engineering in particular, and introduces foundational terminology such as distributive and transactional fairness. Section 3 develops the distributive fairness framework for road traffic engineering. Sections 4 and 5 showcase the application of the framework at the examples of signalized intersection management, and static road pricing. Section 7 concludes this work with a summary.

2. Literature Review

Discussing fairness is challenging, as there is no consensus on a clear definition, and defining fairness heavily depends on social and cultural contexts. In the context of traffic engineering, previous works on fairness are limited in that the studies: (i) mostly discuss fairness in a qualitative rather than quantitative way, (ii) are limited by Egalitarian ideology, (iii) are not connected to fairness literature, (iv) solely employ crude, oversimplifying metrics that measure the distribution's dispersion (mostly standard deviation of delays), and (v) focus on the situation of vehicles/drivers only, overlooking the negative externalities of traffic on residents or other stakeholders [8,9,16,25–36]. Hence, there is the necessity for more systematic, quantitative research on fairness, and a dedicated framework to connect traffic engineering and the modern fairness literature is necessary to involve considerations from multiple ideologies' point of view.

In the first part of this section, we identify fairness as a requirement for cooperation, highlight fairness as an evolved trait of social animals in large populations, discuss the backgrounds of this term, and demarcate fairness against equity, equality, and justice. The second part reviews previous work on fairness in transportation planning, discourses on political, and social justice movements related to road transit, and elaborates on one of the most recognized fairness theories in the transportation domain: "transportation justice". The third part systematically reviews and compares the few previous works on infrastructural and behavioural control in traffic engineering that discuss equity issues and highlights the limitations of these works.

2.1. Fairness

2.1.1. What Is Fairness?

A discussion of fairness is challenging, in general, as fairness is an intangible, philosophical idea that must be discussed specific to social and cultural contexts. More than two millenniums of philosophical discussions across different human civilizations have not yet resulted in consensus [44]. What is more, the many theories on fairness in the philosophic & political-philosophic discussion are rather transcendental, transitive-comparative at most, and qualitative in nature, which is of little help for traffic engineering purposes [37]. Often, fairness is a question discussed when resources are distributed [45].

From an evolutionary biology point of view, sensitivity to fairness is a behavioural trait that evolved in social animals, whose survival depends upon cooperation in the context of a social group. The perception of fairness can be observed for many social animals that live in large populations, such as vampire bats [46], capuchin monkeys [47], and humans [48]. On the individual level, the subjective perception of fairness is found to be important for the psychological well-being [20] and physical health [21]. Social brains react to the lack of fairness with a feeling of disgust, triggered by the insula [48], where the reaction is stronger for a subjectively perceived, unfair disadvantage compared to an unfair advantage. Moreover, perceived fairness affects how individuals engage in relationships and interact with each other [49]. On a population level, fairness is fundamental to building strong communities amongst individuals, to encourage cooperation and social rule-following [20]. Shared, tribe-specific norms and culture determine the perception of fairness [50]. The perception of fairness is not only happening on the individual level, but it is also described as an emergent, cognitive phenomenon on a population level [51]. What is more, fairness strengthens social cohesion, reinforces identification and trust with the group, reduces conflicts, and yields higher (economic) outcomes [49].

Fairness is considered as the foundation for human cohabitation, and therefore widely discussed in philosophy, ethics, sociology, politology, economics, and religion science, as a multidisciplinary term. Fairness is a hypernym for equality that refers to an allocation where each individual is given the exact same amount of resources (egalitarian fairness ideology), neglecting contribution, need, preferences or utility. The terms of fairness, equity and justice are used interchangeably in the literature [44]. Equity is a terminology for fairness that is predominantly used in economic considerations. Justice is a terminology for fairness that appears in political debates, such as the social justice and environmental justice movements. For an extensive overview on fairness, the reader is recommended to review [44]. In this paper, we use "fairness" as the overarching term for the conceptual and quantitative discussion of distributive mobility resource allocation in traffic engineering.

2.1.2. Transactional Framework of Distributive Fairness

At its core, fairness (and especially distributive fairness) is a question of allocation (distribution) of resources across a population as a result of transactions. Resources do not only include desirable, value-generating resources but can also refer to undesirable resources with negative value, to burdens, or to penalties. This is why fairness discussions are often of a distributive nature [37]. The fairness perspectives ex-post and ex-ante describe what matters for the fairness of a resource allocation; the first one focuses only on the output of a transaction, the second one focuses only on the input of a transaction, and of course a combination of both is possible [44].

Following the Aristotelian, Nicomachean, transactional fairness theory, fairness discussions can be grouped into dianemetic and diorthotic fairness [43], as outlined in Figure 1. Transactions can be interactions between different types of parties under different circumstances; this can include trades on markets, endowment of resources from government to population, participation in governmental decision-making processes, or a court tribunal. Dianemetic, distributive fairness is concerned with transactions in which a population is endowed with resources from an authority. Usually this discussion is concerned with governmental institutions that endow a population, for example, in the case of subsidies or societal redistribution processes. The initial situation can also be considered as an endowment. Diorthotic, commutative fairness is concerned with transactions between individuals (or groups) of a population, which usually includes trades on markets.

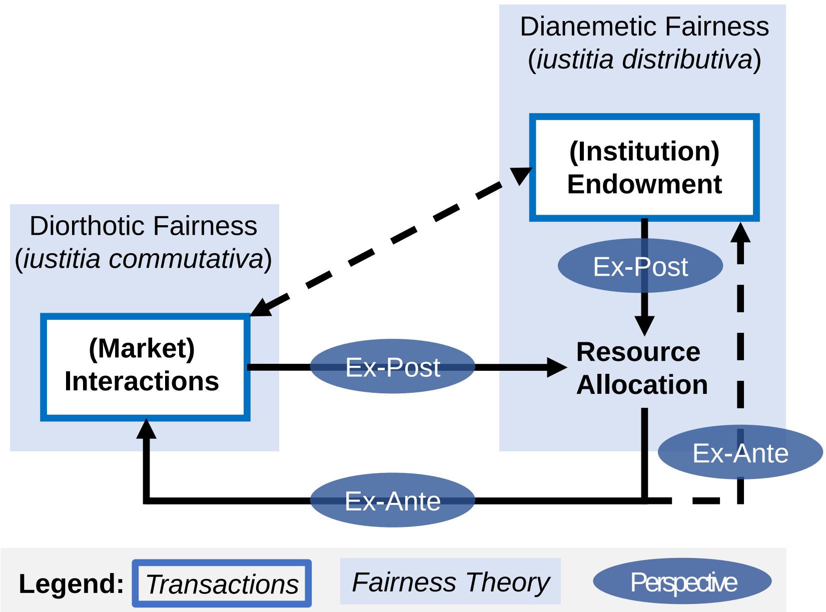

Figure 1. Transactional Fairness Framework. The Aristotelian, Nicomachean, transactional fairness theory discusses fairness in the context of resource transactions, and differentiates dianemetic and diorthotic fairness. Diorthotic fairness refers to transactions as interactions between individuals, e.g., on markets. Dianemetic fairness refers to transactions from an authority to a population, e.g., governmental resource distribution.

2.2. Fairness in Transportation Planning

Transportation shifted from a luxury into a necessity in industrialized societies [52]. Access to transportation resources is vital for a meaningful, joyful, fulfilling, and dignified life, as it enables access to the job market, recreational activities, social participation and marketplaces [1]. Transportation justice is the consideration of fairness in questions of transportation, and evolved from the fields of social justice and the civil rights movement [53,54]. Political, activist movements in California (transportation justice movement of Los Angeles), Atlanta (pray for transit), and Flanders in Belgium (basic accessibility debate) were recognized and inspired by the political philosophy literature of the recent [55,56].

The discussions on fairness in transportation can be grouped into (i) descriptive works that report disparities and the disadvantagement of specific groups (by race [1,15,57], economic power [56,58,59]), and (ii) prescriptive, reformative works that advocate new forms of transportation planning [52,55] and transportation system designs in favour of transit or active modes (cycling, walking) [60]. Additionally, (iii) works elaborate on land-use [14,61,62], emissions, public health & environment [63,64]. A central concept that appears in most works is accessibility and potential mobility; moreover, focussing on public transport is a common narrative.

Karel Martens' pioneering work "Transport justice: Designing fair transportation systems" [52] is one of the most recognized fairness theories in the transportation domain. Martens bridges the gap between political-philosophy theories on fairness (Walzer's spheres of justice, Rawls' difference principle, and Sen&Nussbaum's functional capabilities approach) and transportation. His work contributes threefold: (i) it criticizes traditional cost–benefit analysis, (ii) it proposes a new form of transportation planning that emphasizes a strong involvement of disadvantaged groups in the planning process, and (iii) it advocates the concept of accessibility and Sufficientarianism. Traditional cost–benefit analysis follows a utilitarian approach, aiming to maximize the benefits of the greater good (e.g., by considering minimal waste of value of time). Martens argues that this approach has a systematic bias, as it neglects that demand choices follow supply patterns, and hence reinforces economic inequalities by favouring high-income minorities in an undemocratic manner. Following Walzer, Martens identifies the social meaning of transportation goods in two concepts. Potential mobility refers to the ease with which a person can move through space. Accessibility refers to the potential of opportunities for interactions. Connecting these concepts with the Rawlsian, Dworkian and Capabilities approaches, he argues that the assessment of fairness shall be first and foremost a measurement of accessibility. Finally, he proposes a Sufficientarian [65] theory of fairness for transportation, where a critical minimum of accessibility (the sufficiency threshold) must be guaranteed for each member of the society. However, he leaves the definition of a sufficient threshold open and argues it must be determined and discussed in a democratic process.

While most initial works were rather qualitative, transcendental and comparative in nature, proposed quantitative measures for transportation planning become increasingly sophisticated in the transportation justice literature [1]. The accessibility concept has been quantified in different measures, such as the potential mobility index [14,52], the logsum-based access measure [66], a measure that captures supply and demand of shared mobility [67], a measure for home delivery services [68], and measures in the context of the 20 min city [69]. Moreover, the maximum necessary travel time, distance, and expense to reach relevant locations for all residents of a specific area were discussed in [54].

2.3. Fair Traffic Engineering

2.3.1. Fair Infrastructural Control

A comparative summary of the few works from traffic engineering that explicitly approach fairness in infrastructural control can be found in Table 1. Most works identify the distribution of delays and queue lengths as relevant to fairness, which implies distributive fairness considerations [33]. Additionally, there is an ongoing debate on the relationship between efficiency and equity. Some works find a goal conflict and, thus, argue one must trade-off between efficiency and equity [31,35,70–72]. Contrary to that, others do not find that efficiency and fairness necessarily play a zero-sum-game [8,33,73]. In addition to that, several works draw parallels between computer science and network engineering, and employ metrics from these domains, most prominently Jain's equity metric [16,31,74]. What is more, previous studies [16,35] emphasize the importance of perceived rather than factual delays, and advocate forms of weighted delay optimization where shorter delays are considered under-proportionally important when compared with longer delays.

In the context of signalized intersection management, the distribution of delays is central to fairness considerations and usually fairness is understood as minimizing the standard deviation of delays [16,25–27]. Raies et al. [27] distinguishes time delays of vehicles, and green times of movement phases. Moreover, the distribution of queue lengths is also taken into account [28,29], and fairness is understood as adherence to a scoping range for the queue lengths. Hendriks et al. [16] contrasts a variety of equity measures and links how aspects of traffic light control algorithms correspond to certain theories of fairness.

In the context of ramp metering, Levinson et al. (2006) [75] differentiates temporal (different freeway entrance times) and spatial (different on-ramps) inequity of delays. Levinson et al. (2004) [35] does not explicitly measure fairness in order to integrate fairness into optimization, rather they apply a non-linear function to weight delays, where longer delays have a stronger weight than shorter delays. Meng et al. [30] considers a spatial equity index, where delays of different ramps rather than different vehicles are considered. Dispersion of delays is used to assess fairness in [8,33,34]. Amini et al. [31] considers a Nash bargaining solution and [32] investigates spatial variation.

In the context of perimeter control, distribution of delays and queue lengths are considered as relevant to fairness. Alpha-fair [9,36] balance queue length and delay distribution as part of their perimeter control optimization to emphasize the importance of equity.

In addition to to infrastructural control as such, recent works also explore the equity of intelligent transportation and mobility systems that include vehicle-to-vehicle and vehicle-to-infrastructure coordination, and explore the potential of autonomous cars [24]. Khele et al. [76] explores equitable coordination of electric vehicles and smart charging infrastructure, and [77] explores equitable coordination in intelligent, multimodal transportation systems. A common narrative in this strand of research is the development a mobility equity metric inspired by previous transportation planning works, relating to accessibility as an interpretation to equity [24,77].

Table 1. Works on Fair Infrastructural Control.

Traffic Engineering Control System	Distributed Resource	Fairness Metric
Signalized intersection management	• Vehicle delay [16,25,26] • Movement phase delay [27] • Queue length [28,29]	• Standard deviation [16,25–27] • Range [27]
Ramp metering & (Variable) speed limits	• Ramp delay [30] • Vehicle delay [8,31–34] • Weighted delay [35]	• Spatial equity index [30] • Gini coefficient [8] • Nash bargaining solution [31] • Spatial variation [32] • Various dispersion metrics [33,34]
Perimeter control	• Vehicle delay [9,36] • Queue length [9]	• AlphaFair [36] • Dispersion [9]

2.3.2. Fair Behavioural Control

In this section, we review the works from traffic engineering that explicitly approach fairness in behavioural control. Behavioural control, including economic instruments such as congestion pricing, express toll lanes, license plate rationing, or tradeable mobility permits, intersects a lot with the field of transportation planning in that these are often transportation policies. In this work, we consider behavioural control as traffic engineering, as it is achieved by sensing, actuating and controlling a given infrastructure, and can be realized in the short-term rather than the long-term (as is the case for planning).

Fairness-related works on fair behavioural control agree that equity concerns and related public acceptance issues are the *Achilles Heel* of behavioural control, and emphasize the need for more fairness-related studies [78–81]. Rather than analysing the impact on factual fairness, many works actually analyse perceived fairness through survey studies [10,79,82,83]. Most studies discuss whether economic instruments in the context of behavioural control are fair at all from a qualitative perspective, and avoid discussing the quantitative question of a fairness-maximizing price at all.

In the context of tradeable mobility permits, Fan et al. [84] reviews the inequities between different groups (gender, age, district, income) and takes inspiration from transportation justice ideology. Bogenberger et al. [85] studies the fairness of tradeable mobility permits in the context transportation economics & planning aspects such as public infrastructure financing.

In the context of rationing, fairness is analysed by the dispersion of travel times [86,87]. What is more, previous works document how behavioural control gets circumvented by wealthy individuals and black markets, which is problematic from a procedural fairness point of view [87,88]. In an extensive literature review, Yu et al. [80] shows that almost none of the prior works on rationing analyse fairness in a quantitative way. Wang et al. [89] presents a survey on the perceived fairness and contrasts lottery- and auction-based rationing systems.

In the context of express toll lanes, three forms of fairness are distinguished: income fairness, geographic fairness and modal fairness, where income fairness is the aspect of highest attention in public debates [90,91]. What is more, a differentiation between horizontal equity (fairness within groups of similar individuals) and vertical equity (fairness between different groups), as well as a classification into market, opportunity and outcome equity is made [81]. Road pricing, in general, is considered as regressive taxation, which means it burdens the poor relatively more than the rich [92]. Schweitzer et al. [93] compares road pricing with other forms of regressive taxation finding that taxes that are hard to subjectively perceive, such as sales tax, cause less resistance in the public. Karlstrom et al. and Zhi et al. [94,95] study fairness quantitatively by assessing the dispersion of costs across the population. Eliasson et al. [96] approaches fairness by analysing the distribution of welfare.

In addition to what was found in the fairness-related express toll lanes literature, in the context of congestion pricing, studies discuss the potential remedies of price differentiation [94,97]. Furthermore, Ecola et al. [98] considers additional stakeholders such as residents and retail shops in the fairness debate. Instead of asking whether congestion pricing is fair, Manville et al. (2018, 201) [99,100] ask whether free (unpriced) roads can be considered fair instead and refer to the pricing of other infrastructural utilities such as water, electricity, gas or even food, where pricing is not considered as unfair. Another branch of research is concerned with socially more feasible, more equitable alternatives to monetary markets that still serve as economic instruments and incentive mechanisms. These alternatives include tradeable credit schemes [5] (cap and trade mechanisms) and artificial currencies such as Karma [101–104] and MobilityCoin [105].

To summarize, most fairness-related works in the field of behavioural control are choosing a qualitative rather than quantitative way, and the few quantitative works are limited to an egalitarian discussion related to the dispersion. A connection to modern fairness theories is clearly missing.

3. A Framework for Fair Traffic Engineering

The distributive framework aims to enable quantitative discussions on fairness in traffic engineering by a unique connection between philosophical fairness elaborations and algorithmic traffic engineering solutions. After defining purpose and properties, we demarcate the framework from the field of transportation justice. Next, we identify relevant philosophical ideologies and moral guiding principles for the discussion at hand and propose tools to quantify fairness. Then, we outline how traffic engineering solutions can be modelled as resource allocation mechanisms, determine fairness-relevant resources, and connect these insights with the ideologies. Figure 2 summarizes the structure of the proposed framework.

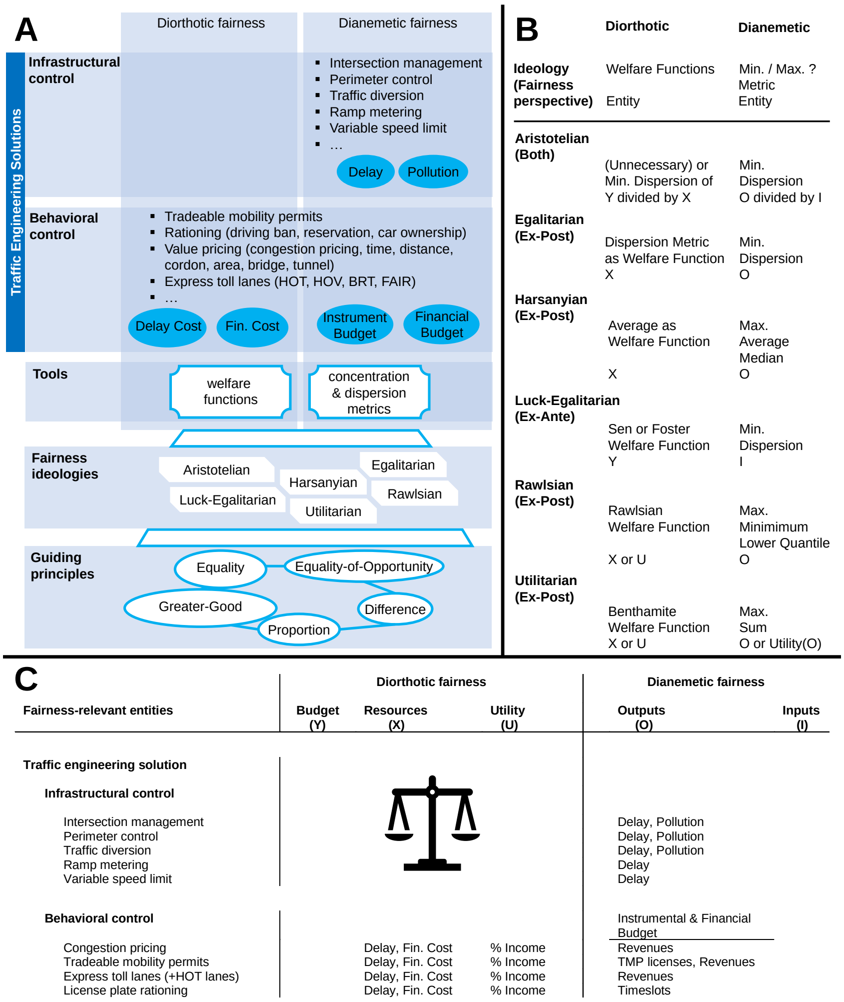

Figure 2. Framework: Distributive Fairness for Traffic Engineering. (**A**) Traffic engineering solutions and fairness-relevant resources in the context of diorthotic and dianemetic fairness, based on tools from statistics and welfare economics to assess fairness based on ideologies and guiding principles. (**B**) Fairness-quantifying metrics of resource allocation problems for distributive ideologies. Diorthotic (X = resources, U = utility, Y = income) and Dianemetic (O = Outputs, I = Inputs) metrics for relevant ideologies. (**C**) A projection of the fairness quantification to the problems of traffic engineering. This table outlines fairness-relevant, teleologic entities for different infrastructural and behavioural control solutions.

3.1. Purpose & Properties

The proposed fairness framework is developed for the domain of traffic engineering and shall serve two purposes: (i) it shall be useful when designing traffic engineering solutions in terms of fairness without sacrificing transportation efficiency; (ii) it shall be convincing and equip traffic engineers with an urgently needed, useful, argumentative tool-set to confront equity considerations in public debates.

To serve these purposes, the framework must discuss fairness in a quantitative, ideology-free, distributive, and pragmatic way. A quantitative discussion of fairness enables the integration of fairness in the optimization problems of the automated, algorithm-driven approach of traffic engineering and cybernetic societies in a broader sense [37]. A conceptual, transcendental discussion of fairness is insufficient. In order to be convincing, the framework must be ideology-free and allow for the integration of various different fairness ideologies, rather than advocating a specific one. This allows for a holistic and systematic analysis of fairness from different conceptual perspectives. For a quantitative discussion, we choose to model traffic engineering solutions as resource allocation mechanisms and focus on teleologic, distributive fairness ideologies. In order to be of value, efforts to improve fairness must be pragmatic and cannot come at the cost of transportation efficiency or cause even more congestion than there already is.

3.2. Demarcation Against Transportation Justice

The framework addresses traffic engineering that is fundamentally different from the commonly discussed fairness aspects in transportation justice, which relates to transportation planning, accessibility, and potential mobility. While conventional transportation planning disregarded the improvement of public transportation systems in favour of investments into individual mobility in the form of road transportation systems in many parts of the world, traffic engineering is limited to controlling existing road transportation systems only. From this point of view, our framework is of little use to contribute to any questions related to planning and public transportation expansion. At most, it can attribute public transportation with dedicated lanes or privileged treatment in control algorithms to achieve transit prioritization. The authors and the proposed framework fully agree with the valid concern of the transportation justice movement: *"accessibility shortfalls caused by congestion are as much an injustice as accessibility shortfalls caused by inadequate public transport services or any other cause"* (Karel Martens [14]).

3.3. Relevant Fairness Ideologies

Many different ideologies (schools of thought) evolved in the history of ethics and philosophy; disparities and fairness do not necessarily exclude each other and are rather advocated to a certain extent. While all ideologies have their argument, they differ in their specific interpretation of what fairness means [44]. We identified six ideologies and five guiding principles on fairness, which are particularly useful for this distributive framework, and propose their use for quantification: Aristotelian (proportion principle, also called Aristocratic), Utilitarian (greater-good principle), Rawlsian and Harsanyian (difference principle), Egalitarian (equality principle), and Luck-Egalitarian (equality-of-opportunity principle) ideology. The proportion principle [44] describes an allocation as fair, as long as it is proportional to the status of individuals. The status could reflect the individual's contributions (e.g., tax paid, income, economic power) or could reflect the individual's need (e.g., urgency). The greater good principle [106] describes an allocation as fair, as long as it maximizes the greater good of the society. This can also imply the sacrifice of the few for the benefit of the many. The difference principle describes an allocation as fair, as long as it achieves the best possible outcome for the least-advantaged

(Rawlsian) [39] resp. the best possible average outcome (Harsanyian) [107]. The equality principle describes an allocation as fair, as long as it achieves equality of endowment [44]. The equality-of-opportunity principle [108,109] describes an allocation as fair, as long as the initial chances/opportunities of each individual as inputs to a (stochastic) societal process have been equal. For sure, the application of these ideologies must be discussed in the context of a specific resource allocation problem, and not all of these ideologies might equally well apply in every context. We excluded Sufficientarianism from our discussion, as it introduces the complexity of finding a sufficient minimum and leaves even more unanswered questions during implementation.

3.4. Quantifying Dianemetic and Diorthotic Fairness

In order to translate the qualitative ideologies to quantitative metrics, we propose the use of Welfare functions for diorthotic, and concentration and dispersion metrics for dianemetic fairness elaborations, as formalized in Figure 2. In terms of dianemetic fairness, ideologies differ in their perspective on the relevance of individual outputs O and inputs I to a resource allocation process. The inputs I can refer to contributions or social status (Aristotelian) or to starting conditions (Luck-Egalitarian). The outputs O can refer either to allocated resources or the actual utility the resources have to the individuals. In terms of diorthotic fairness, a discussion on market equilibria and welfare economics is proposed. Market equilibria emerge from a resource allocation process in a population of individuals with a free will that aims to achieve the best possible outcome for themselves (rationality assumption). In this context, each individual possesses a budget y, to acquire resources x via transactions that generate a certain utility u for the individual, depending on its personal preferences and utility functions. One can stress Market equilibria towards Welfare-maximizing optima, for example, by introducing (redistributive) taxation or pricing. These optima are located at the tangential point of bliss between Pareto-efficient, market-equilibria frontiers and welfare functions. Welfare functions define the understanding of what welfare is and can be tailored to reflect fairness considerations and, depending on the ideology, include allocated resources x, budgets y or utility u.

3.5. Modelling as Resource Allocation Mechanism

Traffic engineering can be considered as the allocation of spatio-temporal resources. Infrastructural control can be considered an institution in the context of dianemetic fairness. Behavioural control has both components: the diorthotic component to assess whether the (market) interactions between users and resulting market equilibria are fair and the dianemetic component to assess whether the initial endowment can be considered fair (a prerequisite for fair, diorthotic transactions) [110]. In order to discuss distributive fairness in the context of traffic engineering, fairness-relevant resources and actors must be identified. With regard to philosophic theory, we find which criteria can be used to determine the relevance to fairness. Rawls argues that primary goods, which are of interest and affect utility for every human–independent of their preferences–are relevant to fairness [39]. Walzer argues that goods with a distinct social meaning need to be distributed in dedicated, fair, distributive spheres, contrary to normal goods [40]. The capability approach advocates discussing resources that determine capabilities (freedom of choice through many opportunities) rather than functionings (actual outcomes) [41,42].

In the context of infrastructural control, we consider delays and pollution as fairness-relevant resources. Delay can be considered as the difference between the free-flow travel time and the actual travel time a user experiences. Plain delays, perceived delays (over-proportionally increasing with longer durations), as well as delays per travelled distance, can be subject to discussion. Delays are undesired by every rational passenger, cause costs to them (negative utility depending on urgency) to accumulate to a significant amount of life-time and, ultimately, result in lost opportunities. Traffic-related externalities (pollution) cause damage to health and the environment (noise, emissions, safety), and affect location-specific inhabitants (and people living or working there) rather than vehicle drivers.

In the context of behavioural control, we consider financial and delay costs (diorthotic), and financial and instrumental budgets (dianemetic) as fairness-relevant resources. Behavioural control instruments incentivise a change in the choice behaviour of users (modality, route, timing, and temporal scope) in order to overcome selfish preferences and to achieve more desirable decisions (on a system level). The modality choice refers to the means of travel (e.g., single car, carpool, public transport, staying at home). The route choice refers to the route of travel (e.g., a tolled but fast highway vs. taking a free but slower route). The timing choice refers to when certain travels are conducted (e.g., on-peak vs. off-peak hours) and the choice of starting times. The temporal-scope choice refers to the trade-off between present and future delay costs. Behavioural control solutions achieve a change in choice behaviour by introducing financial costs to the users, allowing them to trade-off financial and delay costs on a market-like process from a diorthotic point of view. Budgets can refer to financial means, but they can also refer to instrumental budgets, such as ration cards and permits, redistributed monetary revenues, or artificial currencies. Financial means are usually determined by labour work opportunities; both can usually be seen as fixed on the short-term perspective and are observed to be significantly unequally distributed in most modern populations. Due to the temporal horizon of traffic engineering, one could therefore argue that dianemetic discussions are rather related to transportation planning than to traffic engineering. However, deftly designed behavioural control instruments and redistributive measures can address these equity issues as well.

We advocate context-, resource- and investigation-specific scoping when defining fairness-relevant actors. In general, we argue that the ultimate goal must be a fair distribution of relevant resources across single users. In practice, however, an aggregated view on vehicles or vehicle groups might be more feasible and pragmatic. For example, this could involve a discussion on vehicles of the same type (e.g., public transport vehicles, bicycles, delivery vehicles), or vehicles of the same origin (e.g., vehicles from a certain suburb or region that go to the city), or vehicles of the same purpose (e.g., work commute, recreational). Moreover, depending on the resource discussed, different relevant actors or actor groups must be identified. For cost resources with negative utility, namely externalities of road transportation such as pollution, users that experience the costs should be considered. For pollution, it is less the users of a road transportation network and rather specific locations or local habitant groups that need to be taken into account, which implies further external stakeholders such as residents or retail shops.

3.6. Projection of Fairness to Traffic Engineering

We made two important observations when applying quantitative measures for dianemetic and diorthotic fairness to the context of traffic engineering. First, we do not see any fairness-relevant resources that could be considered as an input (I and y_i) to a resource allocation process and could be addressed by existing traffic engineering solutions. However, in future systems with autonomous and fully connected vehicles, inputs such as bids for auction controllers could be possible. Thus, only teleological (ex-post) fairness theories apply, and Aristotelian and Luck-Egalitarian ideologies are excluded from this discussion. Second, a discussion on delay, pollution and financial cost resources deviates from usual fairness discussions in that they are of negative utility to the users.

While delay and pollution resources could be discussed for any infrastructural control system, we argue that pollution is usually a concern in control applications in the urban context, meaning intersection management, perimeter control and traffic diversion only. Delays can be translated to monetary values using the subjective value of time (VOT), which allows the trade-off with financial costs. These cost resources could be translated to utilities in order to discuss costs as standardized monetary values of the income (share of income).

Instrument-specific budget resources could refer to entities such as licenses in the context of tradeable mobility permits and timeslots in the context of license plate rationing. What is more, generated revenues (from congestion pricing, express toll lanes, and tradeable mobility permits) could be redistributed across the population and would thus affect the financial budgets. These generated revenues could also be invested into public transportation and would thus affect available alternatives.

3.7. Application

The application of the framework for a fairness discussion is depicted in Figure 3. Starting from a traffic engineering problem (1), one needs to determine dianemetic or diorthotic transaction type (2), choose relevant fairness ideologies (3), determine process users (4) and resources (5), and choose quantitative measures to assess equity (6). The individual steps are supported by the preceding subsections.

- Step (2) can be guided to determine the right transaction type, given the traffic engineering problem, by the mapping presented in the framework (Figure 2 and Section 3.6).
- Step (3) should be guided by the type of control problem and the normative concern under investigation (see Section 3.4). Utilitarian and Harsanyian perspectives are suitable when the collective or average burden is central; Rawlsian perspectives are suitable when the worst-served users or modes are of concern; egalitarian perspectives are suitable when the dispersion of burdens is the main concern; Aristotelian and Luck-Egalitarian perspectives become relevant when meaningful input variables, such as contributions, budgets, opportunities, or ability to pay, can be identified.
- Step (4) requires a context-specific scoping decision (see Section 3.5), while the ideal unit of analysis may be the individual road user, practical applications may use aggregated actor groups such as modes, vehicle classes, origins, regions, corridors, trip purposes, or affected residents.
- Step (5) follows the resource-allocation interpretation developed in Section 3.5: infrastructural control primarily allocates delay and externality burdens, while behavioural control allocates combinations of delay costs, financial costs, and instrumental or financial budgets.
- Step (6) follows from the selected ideology and resource: welfare functions are suitable for diorthotic market-like settings, while concentration and dispersion metrics are suitable for dianemetic allocation settings (see Section 3.6).

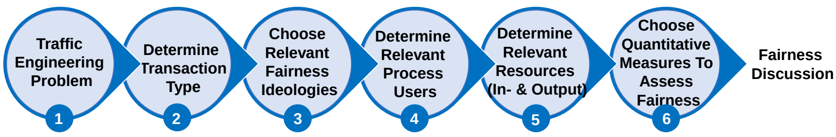

Figure 3. Six Step Approach For Fair Traffic Engineering.

4. Case Study

In this section, three case studies serve as demonstrations for the usefulness of the proposed fairness framework and outline how the framework can be used to inform control system design on enhancing fairness while preserving efficiency. The case studies discourse both infrastructural and behavioural traffic engineering control solutions.

At the beginning of the section, the three case studies are presented in more detail, and the specific fairness measures to investigate fairness are outlined. In the following, details on traffic microsimulations and game theoretic market simulations are outlined. Further details on the case studies are outlined in the Appendices A–D.

4.1. Case Study 1: Dianemetic

The first case study shows how dianemetic fairness can be taken into account when designing signalized intersection management as outlined in Figure 4. The static design problem is concerned with an uncoordinated, fixed-cycle traffic light controller with two integer parameters (representing green phase durations of straight and turning movement phases). The setup can be considered as a dianemetic institutional endowment (allocation of delay resources) by the traffic light. The discussion in this case study is focussing on the motorized road users to showcase a teleological (ex-post) fairness discussion from an utilitarian, egalitarian, Rawlsian, and Harsanyian perspective, following the recommendations of the proposed framework. Aristotelian and Luck-Egalitarian ideologies are excluded from the discussion of this case study, as accounting for differences in the heterogeneous road user population is not possible, as no fairness-relevant resources were identified that could be considered as an input (I and y_i) to the delay resource allocation process, and conventional traffic light controllers usually do not possess information about vehicle and driver heterogeneity for differentiation purposes. Aristotelian and Luck-egalitarian fairness could be applied to dianemetic traffic control, though, when meaningful input variables are available; for example, in connected-vehicle, bidding, credit-based, or priority-aware control systems of the future.

The case study employs a Manhattan-like road network that consists of nine intersections that are connected with four-laned, bi-directional, 100 m long roads (Figure 4A). Each intersection is equipped with a fixed-cycle traffic light and four distinct movement phases. The transition from one to the next movement phase takes 3 s of transient yellow time for safety reasons (Figure 4B). The road network has twelve entrances and exits. An equal, static traffic flow at each of the entrances is generated, and spawned vehicles are randomly assigned one of the twelve possible routes with an even probability distribution (Figure 4C). Two design parameters for the traffic light controller span the solution space: the green durations of the straight and turning movement phase. Each parameter is varied from one to 40 s. Equal parameters for each intersection are assumed, due to the network symmetry. In order to enable a more fluent traffic, time-shifts are applied between neighbouring cycles; the time-shift equals the average of the parameters.

Following the conventional, efficiency-driven paradigm of traffic engineering, this controller would be optimized using traffic microsimulations (based on historical data), enabling the identification of optimal values for the two integer parameters. A common measure for the transportation efficiency of intersections is the number of passing vehicles per time unit (throughput or flow). Following the informed approach of the fairness framework and the formulation in [37], the fairness measures in Table 2 (It should be noted that some of these fairness measures overlap with conventional efficiency or performance indicators in traffic engineering. Therefore, the proposed framework should not be interpreted as suggesting that fairness and efficiency are always separate or opposing objectives. Instead, the relationship between fairness and efficiency depends on the selected fairness ideology and could be employed as goal functions G for the optimization, where n represents the number of users, and x_i represents the delay that is experienced by road user i, and t_i represents the total travel time that is experienced by road user i. The Gini-Coefficient [111] is a dispersion metric ranging from 0 (perfect equality) to 1 (perfect inequality) that assesses how equally distributed a resource is and, thus, represents egalitarian fairness ideology.

The total travel time is a measure that reflects the collective cost of transportation from users' perspective and, thus, represents utilitarian fairness ideology, while various other metrics could be employed. We choose total travel time in this context as it represents the costs of users, while throughput or flow represents the efficiency from a system perspective. The maximum delay represents the worst experience that any possible user could encounter during a trip through the network and, thus, reflects Rawlsian fairness ideology. The average delay represents the average experience and, thus, reflects Harsanyian ideology. Additionally, various other suggested dispersion measures from [37] are collected for this case study.

Table 2. Fairness Measures for Dianemetic Case Study.

Ideology	Metric	Formula (Minimize)
Egalitarian	Gini-Coefficient	$G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\|x_i - x_j\|}{2n\sum_{i=1}^{n} x_i}$
Utilitarian	Total Travel Time	$G = \sum_i^n t_i$
Rawlsian	Maximum Delay	$G = max_i(x_i)$
Harsanyian	Average Delay	$G = \frac{1}{n}\sum_{i=1}^{n} x_i$

4.2. Case Study 2: Diorthotic

The second case study shows how diorthotic fairness can be taken into account when designing economic instruments to influence road users' behaviour as outlined in Figure 5. The case study is concerned with static, economic pricing instruments to influence passenger route choice behaviour.

The road network for this case study consists of two possible routes (e.g., bridges or tunnels) between starting point 1 and destination point 2 that are separated by a river. Route A is shorter but easily gets congested as it is one-laned. Route B is longer, as it requires driving one additional kilometre on each riverbank, but it is two-laned and thus less prone to congestion (Figure 5A). Depending on the traffic flow, the travel time distribution of both routes (Figure 5B) shows that route A is the more attractive route when uncongested but has much higher travel times during congestion. Au contraire, route B's travel time is higher, in general, but more robust for higher traffic flows. As a result, route B becomes more attractive when route A is congested (for a traffic flow around 950 vehicles per hour).

The traffic flow between points 1 and 2 splits as a result across these two routes. The Wardrop equilibrium [112] is a mechanism that describes how such splits take place as the result of collective decision-making in market-like interactions between individuals of a population. Rational users are observed to act selfishly and to choose routes that minimize their own travel time (homo oeconomicus assumption), respectively, travel costs. As a consequence, a population of rational users is observed to form a split where both routes have an equal travel time (respectively travel costs), and there is no opportunity to improve one's situation by changing. From a system point of view, the split can be considered optimal when the total travel time (measure for efficiency) is minimized. For flows larger than 750 vehicles per hour, the selfish behaviour of drivers leads to splits that are sub-optimal from a system perspective and unnecessarily increase both total and average travel time (Figure 5C).

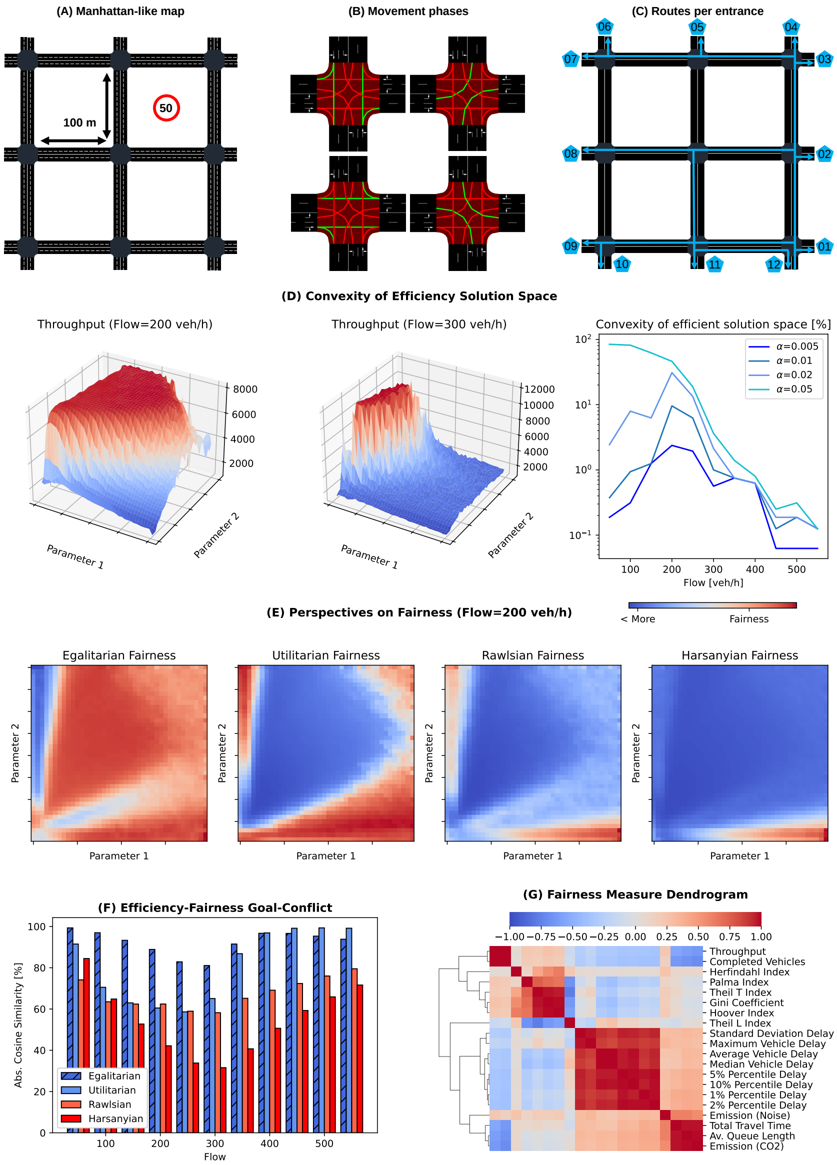

Figure 4. Case Study: Signalized Intersection Management (Dianemetic). (**A**) The Manhattan-like road network for the case study. (**B**) Each intersection is equipped with a fixed-cycle traffic light and four distinct movement phases. (**C**) The road network has twelve entrances & exits. (**D**) Two design parameters for the traffic light controller span the solution space: the green durations of the straight and turning movement phase. The α-efficient space is a subset of the solution space, in which the efficiency equals at least $(1-\alpha)$ of the maximum efficiency possible. The convexity is measured as the ratio of powers of α-efficient and total solution space. The smaller the flows, the higher the room for improvement of fairness. (**E**) Four teleological fairness ideologies measured across the solution space. (**F**) The goal conflict between fairness and efficiency is measured by the Cosine Similarity for different traffic flows (larger Cosine Similarity means fewer goal conflicts). Hatched bars (egalitarian) are negative. (**G**) A metric dendrogram of various recorded efficiency and fairness metrics. The clusters show that the many fairness measures form clusters that correspond to the four underlying fairness theories.

In this case study, the pricing of a bridge is used to control the route choice behaviour (split) of the population across the two available route options. By introducing a toll for the usage of route A, users now do not only take travel times and travelled distance into account, but also financial fees, when making their route choice behaviour based on their total experienced costs when travelling between point 1 and 2. Increasing the price creates an incentive that pushes the Wardrop (user) equilibrium split towards route B (Figure 5E).

The route choice behaviour is linked to the willingness to pay for route A and, of course, is also related to the ability to pay for route A.

This pricing mechanism setup is suitable to illustrate a diorthotic, market-like discussion of behavioural control, as it distributes fairness-relevant cost resources in a decentralized way across the population of concerned, motorized road users. These costs consist of time travelled multiplied with the value of time (VOT, product of urgency and income), distance travelled multiplied with costs per distance, and tolls for the use of road A. Contrary to the first case study, it is possible to include ex-ante fairness ideologies (Aristotelian and Luck-Egalitarian) in this discussion as well, as the fees paid to the system could be considered as the inputs to this resource allocation mechanism.

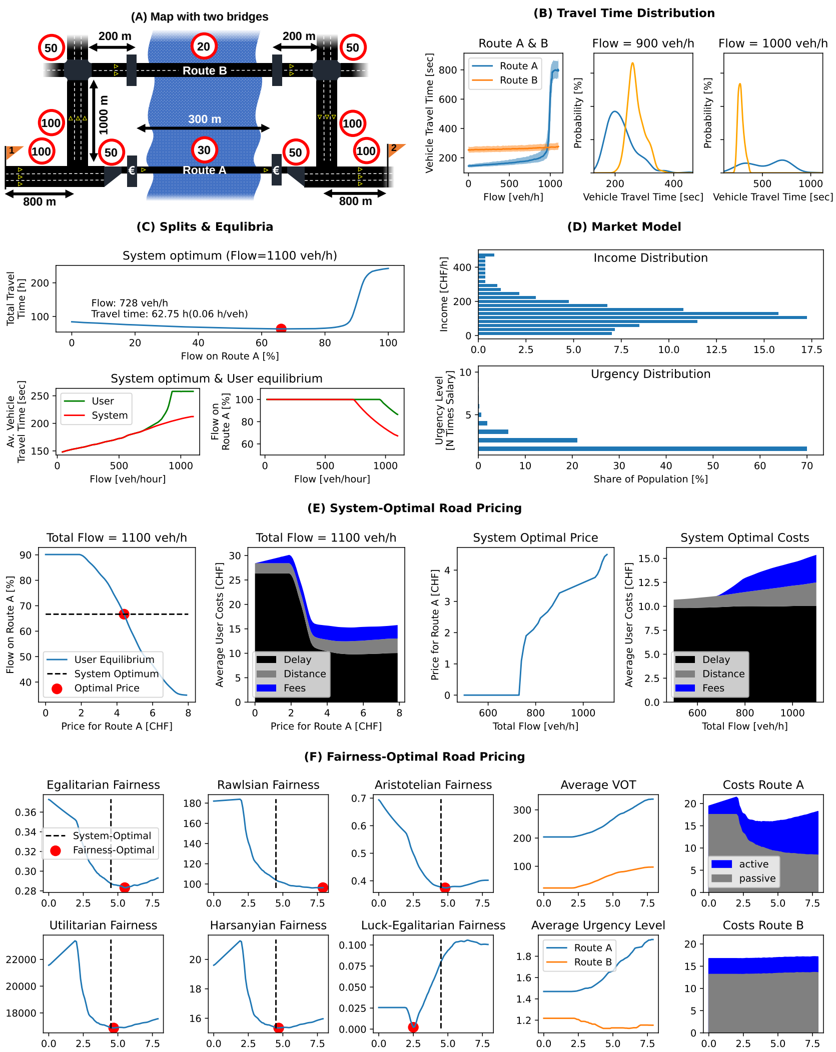

Figure 5. Case Study: Static Road Pricing (Diorthotic). (**A**) The road network for this case study. (**B**) The travel time distribution for each of the two routes at different flows. (**C**) System-optimal splits and Wardrop-equilibrium (user-optimum) splits. (**D**) The market model for this case study, consisting of income and urgency distribution. (**E**) By surcharging a fee for taking route A, users are increasingly incentivised to choose route B. System-optimal road pricing transitions the Wardrop-equilibrium to a system-optimum. (**F**) Fairness-optimal road pricing (lower ordinate values mean higher levels of fairness).

Following the conventional, efficiency-driven paradigm of traffic engineering, this controller would be optimized using game-theoretic market- and traffic micro-simulations, enabling the identification of an optimal price that incentivises just enough users to choose route B over A. In this case study, one could choose the observed total travel time as the efficiency measure. Following the informed approach of the fairness framework and the formulation in [37], the fairness measures in Table 3 could be employed as goal functions G for the optimization, where n represents the number of users, c_i represents the total costs, and vot_i represents the VOT of user i. Moreover, the cost c_i consists of c_i^{ac} and c_i^{ps}, which represent active costs (related to decisions and actions of users, including distance-related costs and fees for the bridge), and passive costs (outcome of the action, cost-related to experienced travel time).

The Gini-coefficient of costs reflects egalitarian fairness ideology. The total travel cost is a measure that reflects the collective cost of transportation from users' perspective and, thus, represents utilitarian fairness ideology. The maximum cost represents the worst experience that any possible user could encounter and, thus, reflects Rawlsian fairness ideology. The average cost represents the average experience and, thus, reflects Harsanyian ideology. The Gini-coefficient (dispersion) of the ratio between active and passive costs c_i^{ac} and c_i^{ps} reflects Aristotelian ideology, as what users (actively) contribute should stand in proportion to what they (passively) receive. Luck-Egalitarian ideology is quantified in a similar manner, taking into account not only the willingness to pay but also the ability to pay, which is why the dispersion of VOT-normalized passive costs is chosen as a measure. The primary concern in Chance-Egalitarianism is ensuring that differences in outcomes are tied to decisions that individuals can control, rather than starting conditions that they cannot control (such as income or urgency), which is why we chose to normalize for VOT (product of income and urgency). The justification to normalize passive costs is that these passive, time-related costs (or delays) are a more direct measure of outcomes, whereas distance and fees are more under control, are less impacted by starting conditions, and are more related to decisions made.

Table 3. Fairness Measures for Diorthotic Case Study.

Ideology	Metric	Formula (Minimize)
Egalitarian	Gini-Coefficient	$G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} \lVert c_i - c_j \rVert}{2n\sum_{i=1}^{n} c_i}$
Utilitarian	Total Travel Cost	$G = \sum_i^n c_i$
Rawlsian	Maximum Cost	$G = max_i(c_i)$
Harsanyian	Average Cost	$G = \frac{1}{n}\sum_{i=1}^{n} c_i$
Aristotelian	Average Delay	$G = G_{egal}(c_i^{ac}/c_i^{ps})$
Luck-Egalitarian	Average Delay	$G = G_{egal}(c_i^{ps}/vot_i)$

4.3. Case Study 3: Vertical Dianemetic (Multi-Mode)

The third case study demonstrates how vertical-dianemetic fairness can be taken into account when coordinating between different modes, as outlined in Figure 6. In this case study, an actuated Max-Pressure controller [113] is used to coordinate the right-of-way at a complex intersection with five different modes approaching: cars, trucks, buses, bicycles, and pedestrians. For this case study, the design problem consists of finding five float parameters, representing the weights of single modes that are used to calculate a movement phase's total pressure. The setup can be considered as a dianemetic institutional endowment (allocation of delay resources) by the traffic light. Similar to the first case study, a teleological fairness discussion from a utilitarian, egalitarian, Rawlsian, and Harsanyian perspective is conducted.

The case study employs a complex 30 m × 30 m intersection with four approaches, including 20 lanes for motorized vehicles, 4 lanes for bicycles, and 4 pedestrian crosswalks. Five different modes, including cars, buses, trucks, bicycles, and pedestrians, are present. We assume 1.5 passengers per car and 20 per bus. Bicycles and pedestrians count as 1 each. For trucks, we assume 10, reflecting not passengers but the societal significance of transporting goods to retail facilities. The traffic light controller switches between four different movement phases that give right-of-way to horizontal movements, vertical movements, or the pedestrian cross-walks. Using sensors, the traffic light controller is able to determine the number of vehicles on each lane and the cumulative waiting time of all vehicles at each approach, except for the pedestrians. For the pedestrians, solely the time since the last button push is recognized. A varying traffic is randomly generated. At regular intervals, the Max-Pressure controller determines the pressure of each movement phase based on cumulative, weighted waiting time and transitions to the phase of highest pressure. Five different weights for the different modes are taken into consideration.

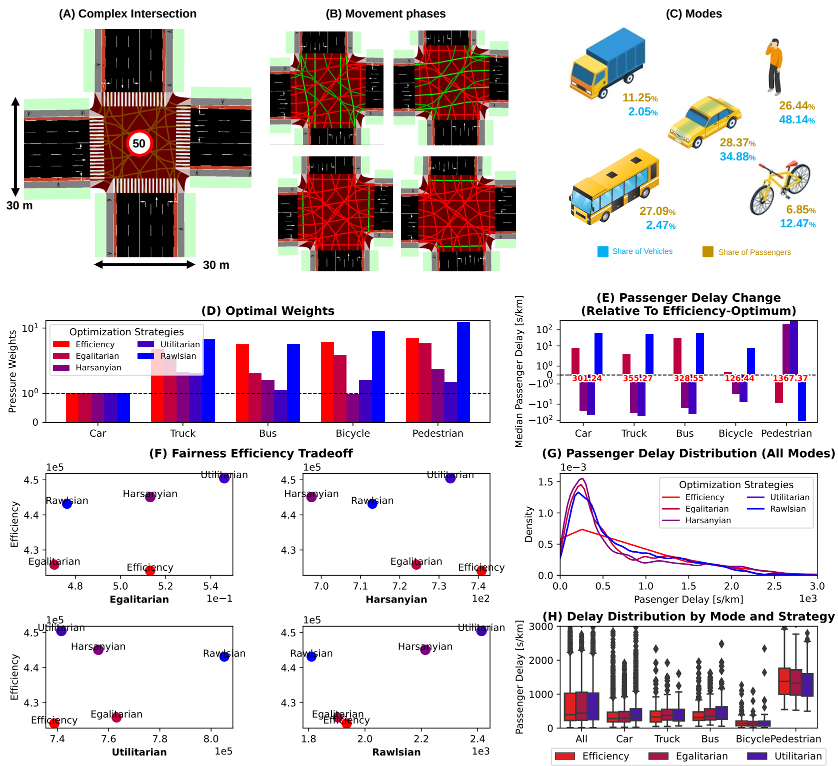

Figure 6. Case Study: Multi-Mode Intersection Management (Vertical-Dianemetic). (**A**) The complex intersection used for the study. (**B**) The intersection's possible movement phases. (**C**) The different modes, and their share of all vehicles and of all passengers. (**D**) Optimal Weights for the Max-Pressure controller for different efficiency and fairness optimization strategies. (**E**) Passenger Delays for different modes and fairness ideologies, relative to the delays in the efficiency-optimal case (Median Delays for efficient-case in red numbers). (**F**) Fairness-Efficiency trade-off for different efficiency and fairness weight optima. (**G**) The passenger delay distribution for different optimization strategies. (**H**) The delay boxplot by mode and optimization strategy.

According to the conventional, efficiency-driven paradigm of traffic engineering, one could optimize the five parameters using microsimulations to determine values that minimize the total vehicle travel time to ensure smooth and congestion-free intersection traffic. Following the informed approach of the fairness framework, we consider rather the passenger travel times t_i and delays x_i. The same formulas from the first case studies are used to quantify the fairness ideologies, as outlined in Table 2. Rawlsian fairness was measured in both, the maximum and 95% percentile to account for the highly stochastic nature of outliers. The procedure to find goal-optimal parameters is oriented on *Next Ascent Stochastic Hillclimbing* [114] for 1000 iterations and ten random seeds each.

4.4. Simulation Models

In both case studies we employ traffic microsimulations to determine and analyse travel time distributions, using the time-discrete micro-simulator SUMO [115]. For the simulation, we use SUMO's standard settings for vehicle. A simulation timestep size of one second was used. Various metrics are recorded during the recording. Vehicles are spawned with an exponential probability distribution ($\lambda = 5$). Each simulation is repeated 10 times with different random seeds, and the average of various collected metrics is calculated in order to mitigate the random effects of the simulation. The simulations consist of a simulation time for transient response before the recording of relevant simulation metrics starts. Ten minutes for the signalized intersection management case study and 60 min for the road pricing case study are used as transient response simulation durations.

The road pricing case study furthermore required a market model (Figure 5D) to calculate the Wardrop (user) equilibrium for the route choice behaviour. Each user possesses two properties: income and urgency level. The income distribution is taken from the wage level distribution provided by the Federal Statistical Office of Switzerland 2018 (https://www.bfs.admin.ch/asset/en/12488554 (accessed on 1 July 2025)). The urgency level represents the number of times a user is willing to pay an hourly salary to save one hour and is assumed to follow a geometric distribution with $p = 0.7$ following [101]. The income distribution and urgency level distribution together form the VOT distribution that lays the foundation for the market model. In the market model, users will choose between the two routes in order to minimize their total travel costs, which consist of time-related costs, distance-related costs, and fees. The time-related costs result from the product of total travel time and VOT. The distance-related costs result as the product of total travelled distance and 0.76 CHF/km milleage cost provided by the Touring Club Switzerland (https://www.tcs.ch/de/testberichte-ratgeber/ratgeber/kontrollen-unterhalt/kilometerkosten.php (accessed on 1 July 2025)). The fees include a price for route A in case this route is chosen by the user and 0 otherwise.

5. Results

The case studies and resulting insights show that fairness and efficiency do not categorically exclude each other and that higher levels of fairness can be achieved without sacrificing transportation efficiency. It can be observed that utilitarian, Rawlsian, and Harsanyian ideologies expose a similarity with transportation efficiency, while egalitarian ideology contradicts the most. A dendrogram analysis of different fairness and efficiency measures reveals meaningful, consistent clusters in the proposed, fairness-quantifying measures that correspond to theoretical fairness ideologies across traffic engineering applications. Balancing modes and whether to focus on transit or pedestrians is where the ideologies disagree the most.

5.1. Dianemetic Signalized Intersection Management

Optimizing the system efficiency (throughput) for different parameter values reveals that efficiency reaches a plateau (Figure 4D). This plateau is large for small traffic volumes and gets smaller for greater traffic volumes. In order to improve the fairness of the signalized intersection management, a secondary, fairness-related optimization goal could be included. When optimizing for transportation efficiency, the α-efficient solution space (efficiency equals at least $1 - \alpha$ of the maximum efficiency) leaves room for fairness considerations, and in cases of lower network saturation allows for significant improvements in fairness without sacrificing efficiency. This, of course, depends on whether fairness and efficiency form a goal conflict and how large the α-efficient solution space (how convex the transportation efficiency) is. The convexity of the transportation efficiency is observed to decrease for larger traffic volumes; hence, fairness improvements can especially be achieved at lower levels of saturation.

Figure 4E shows the parameter space for the four different fairness ideologies as heatmaps, where blue represents more and red less fair solutions. One can observe that the heatmap pattern of utilitarian, Rawlsian, and Harsanyian ideologies resemble to the one of efficiency, while egalitarian fairness contradicts the other ideologies strongly. This observation is consistent with the metric definitions: utilitarian and Harsanyian fairness partly coincide with conventional efficiency objectives, whereas Egalitarian fairness explicitly penalizes unequal distributions and is therefore more likely to conflict with efficiency-oriented optimization.

To better understand, whether fairness and efficiency form a goal conflict or not, and how strong this conflict is, we analysed the absolute cosine similarity between the fairness and efficiency optimization topology, as shown in Figure 4F. Egalitarian fairness is hatched to highlight a negative cosine similarity. The results indicate the previous first intuition, that utilitarian, Rawlsian, and Harsanyian fairness do not form a strong goal conflict with efficiency, and that this goal conflict depends on the road network saturation. Harsanyian fairness ideologies reacts most sensitive to different traffic volumes, while utilitarian and Rawlsian ideology react less sensitive. Throughout all traffic volumes, egalitarian fairness can be observed to consistently form a goal conflict with efficiency. This finding raises the important question, whether egalitarian fairness ideology is a useful and suitable measure when optimizing fairness while preserving efficiency. Even though it is the most commonly used ideology, and in most cases the only ideology, to analyse fairness in this context, the inclusion of other perspectives on fairness seem highly recommendable.

Finally, an analysis of different fairness measures taken from [37] and alternative efficiency measures is conducted by analysing Pearson correlations and outlined in the dendrogram analysis in Figure 4G. The dendrogram exhibits distinct clusters of different fairness and efficiency measures that reflect different points of view on what fairness can be considered as, and more interestingly, if these clusters correspond to fairness ideologies.

5.2. Diorthotic, Static Road Pricing

How can the pricing mechanics of an economic control instrument be used to control the route choice behaviour of the population? To answer this question, we varied the price for route A and analysed the development of costs and travel split between route A and B in Figure 5E. The first plot from the left shows the effect of different prices at a traffic volume of 1100 veh/h and how an (system) optimal price can be determined. Without any pricing (price = 0), almost 92% of all users choose to use route A, causing severe congestion to a point where route A is similarly unattractive (and unuseful in a sense of travel time or travel cost) as route B. Up to a price of 2 CHF, no change in the population's route choice behaviour can be observed, as the incentive is not strong enough to convince a larger share to switch to route B (to surpass the user's reservation price). The users face mileage costs of 1.9 CHF (for route A) and 3.55 CHF (for route B), which imposes certain reservations towards switching. Beginning from a price of 2 CHF, a decline in the usage of road A can be observed. At an price of around 4.5 CHF a system-optimal usage of road A can be achieved. Therefore, this price can be considered a system optimal price. The second plot from the left shows the average user's cost for different prices. In an unpriced setup, the user faces severe delay costs of 25 CHF, as route A is heavily congested and most of the users use this route. Increasing the price causes an increase in total costs first, but beginning from 2 CHF, when the incentive is large enough and more users switch to route B, significant reductions of the delay costs down to 10 CHF (less than half) can be achieved. The distance prices do not make up a large share of the total costs and increase slightly due to the higher usage of route B. Similarly, the fees do not make up a large share of the total costs. The right two plots show optimal prices and costs for different traffic volumes. Below a traffic of around 750 veh/h, the user equilibrium lies at the system optimum, and therefore pricing is unnecessary. Beginning from 750 veh/h, the optimal price starts at 2 CHF (reservation price) and increases with growing traffic volume. With regard to costs that are imposed on the average user, one can observe that keeping the delay costs at a low level comes at the cost of higher distance costs and fees.

How fair is pricing the roads to achieve system-optimal (total travel time-optimal) road usage? To answer this question, we varied the price for route A and analysed the development of various fairness measures in Figure 5F. The six most left plots exhibit the development of egalitarian, Rawlsian, Aristotelian, utilitarian, Harsanyian, and Luck-egalitarian fairness, where lower values refer to higher levels of fairness. An important first observation is that (system) optimal pricing (black dashed line) can be considered as fairness-improving when compared to the initial situation (no pricing). Even though prices below 2 CHF do not sufficiently incentivize a change in route choice behaviour and thus delays, egalitarian and Aristotelian ideologies consider these small prices as fairness-enhancing. From an egalitarian point of view, those using route A are penalized and, thus, increase costs more, similar to those that take the longer route B, which is why all users have more similar costs to face. Similarly, from an Aristotelian point of view, those using route A do not pay enough in an unpriced context, and therefore causing higher costs to those on route A creates a stronger balance between what these users contribute and get in return. The other fairness ideologies, however, agree that only prices above 2 or 2.5 CHF actually enhance fairness.

Interestingly, fairness-optimal prices often lie close to system-optimal prices, and most fairness ideologies agree that too low and too high prices are not good. Conversely, Rawlsian fairness advocates significantly higher prices (the higher, the better). As Rawlsian fairness is focussed on the outliers of the distribution, the maximum cost any user experiences, prices are increased to ensure rare cases of very high urgency levels are satisfied. Harsanyian and utilitarian fairness-optimizing prices match exactly with efficiency (system) optimal prices. egalitarian and Aristotelian fairness ideologies advocate prices that are slightly higher. Luck-egalitarian fairness recommends lower prices at exactly 2.5 CHF when the incentive mechanism achieves to reduce the delay costs most significantly.

The four rightmost plots of Figure 5F describe VOT, urgency, and costs that are experienced by average users of routes A and B. Even in an unpriced situation, distinct differences between the two subgroups of the population can be observed. When increasing these prices, the differences in VOT and urgency on the two routes can enlargened. The total costs and cost composition for users on route B almost do not change for different prices and remain at around 15 CHF, while the total costs for route A users increase slightly to levels between 17 and 20 CHF. The cost composition of users on route A changes significantly as well, where passive costs (experienced time, respectively, delay-related costs) decrease, at the cost of growing active costs (fees and distance-related costs).

5.3. Vertical-Dianemetic, Mode Intersection Management

Multi-mode, signalized intersection management needs to balance various factors, such as efficiency to avoid unacceptably large levels of congestion, but also the experience of vulnerable road users, especially that of pedestrians, to enable walkable and accessible cities for all. An efficiency-driven approach would mainly focus on vehicle delays to guarantee a high throughput of the intersection, while a fairness-driven approach would rather focus on passenger delays. Undoubtedly, public transport and pedestrians might require some form of prioritization, but this means arbitrary delays to motorized vehicles; to what extent are these justifiable? A fairness and efficiency trade-off manifests in this example.

When searching for the right weights for different modes to determine a movement phase is pressure, we run various microsimulations and optimize for specific goals. The outcome of this search process can be found in Figure 6D. The norms were normalized by the weight for cars. Most optimization strategies choose higher weights for all other modes than cars. Moreover, one can observe higher weights, especially for vehicles that need longer times to accelerate after standing and vehicles that need longer times to pass the intersection (e.g., buses and truck). The highest weights are assigned to pedestrians. Harsanyian and egalitarian fairness recommend relatively small weights, while the other optimization strategies recommend higher discrepancies.

The outcome in terms of delays for different modes is displayed in Figure 6E. The black dashed line represents the delays for the efficiency-optimizing strategy, and the coloured bars represent the delay change for different fairness ideology goals. Egalitarian and Rawlsian fairness recommend increasing delays of motorized vehicles to significantly reduce delays of pedestrians, while Harsanyian and Utilitarian fairness recommend the contrary. The potential delay decreases for cars and can be explained by the design of the intersection, where cars, trucks, and public transport vehicles share the same lanes; prioritizing public transport indirectly implies prioritizing cars as well. From a utilitarian and Harsanyian point of view, focussing on the public transport vehicles that carry many passengers seems like the right choice. Contrary to that, egalitarian and Rawlsian ideologies focus on pedestrians, as they experience the longest waiting times compared to the other modes.

A comparison of the various efficiency and fairness optima in the context of a fairness and efficiency trade-off can be found in Figure 6F. The ordinate represents the efficiency, and the abscissas represent different fairness metrics, where smaller efficiency and fairness mean better. In this example, egalitarian fairness achieves similar levels of efficiency as the efficiency-driven approach, while all other fairness-optimal form a group with slightly higher efficiency values.

A detailed breakdown of the passenger delay distribution can be found in Figure 6G,H. A major difference between the efficiency distribution and the fairness distributions is the stronger concentration. When comparing efficiency with egalitarian and utilitarian ideology by modes, one can observe how the efficiency-driven paradigm is in clear favour of cars, while the fairness-driven approach aims to decrease or redistribute delays in favour of all other modes. Pedestrians experience significantly higher delays when compared with other modes. This is because a shift towards the crossings movement phase requires a very long transition and waiting time for all other modes, including the passenger-heavy transit modes, and therefore cannot take place as often.

6. Discussion

In this section, we will elaborate on the applicability of the framework, justify design choices of the framework, and outline how the framework could be used in a multitude of other applications beyond the limited scope of the case studies, in particular how to differentiate between different types of users.

Other fairness-relevant resources: We mostly focussed on delay, pollution, and costs as fairness-relevant resources of interest. Additionally, other resources that could be discussed in future work (but are harder to quantify and to measure) are related to: (i) road safety and risks and (ii) accessibility. Vulnerable road users or the transit might benefit from transit signal pre-emption or significantly shorter waiting times at signalized intersections, for instance. Especially for pedestrians, one of the major determinants of

https://doi.org/10.3390/su18147068

total travel time that can be controlled by fairness-enhanced traffic engineering is the waiting time at signalized intersections. Transition phase durations between movement phase cycles might also affect the safety of vulnerable road users when interacting with motorized users.

Moreover, one could argue that available alternatives are fairness-relevant, dianemetic resources in the context of behavioural control as well. Clearly, the availability of alternatives will determine the decision-making processes of individuals. However, the availability of alternatives, similar to available budgets, is usually determined by the socio-economic contexts of individuals, which is rather in the scope of long-term planning rather than short-term control. Therefore, we restrict our discussion at most to the redistribution of generated revenues to financial budgets. One could argue that on-demand transportation services could be affected by demand patterns in the short-term as well; in this case, we argue, they could be included in fairness-relevant discussions on traffic engineering. For example, modality choice: individuals could either drive by themselves, at the cost of delays, or some of them could switch to on-demand taxi services, at financial costs and potential waiting times if the demand exceeds the taxi-fleet's service capacity.

Other ideologies (Prioritarianism and Sufficientarianism): With regard to the average urgency level of users of route A and B in Figure 5F, one could argue that by enabling users to express their urgency through a willingness to pay, by enabling a market-like coordination of allocating this resource of interest, those in highest need are prioritized, and those are the users the resource is allocated to. This plays an important role in Prioritarian ideology [116], that aims to prioritize and align resource allocations to those in need. Prioritarian ideology, similar to Sufficientarian ideology, was not included into the framework, as these principles might not be so generally applicable as the others.

Prioritarian ideology could be measured as the difference between the average urgency levels between the routes, where it would be considered more fair if this difference got enlarged. Similar to Rawlsian fairness, this Prioritarian ideology would advocate larger prices. Sufficientarianism could be measured by the share of the population that experiences costs below or at a certain threshold, where it would be considered more fair if this share gets enlarged. With regard to cost break-down, we can see that for the average user, through pricing, delay costs, and, thus, the total costs are significantly reduced. Probably, this Sufficientarianism would (depending on the threshold) advocate a price close to the Harsanyian optimum, as no significant further cost reductions for the average user (and thus large shares of the population) could be achieved.

Mode-agnosticism of the framework: In the introduction, it is stated that this manuscript aspires to shift the focus of transportation-related equity discussions towards such discussions between individual motorized road users. This does not mean that the framework is limited to these individual motorized road users, nor does it mean that other discussions are irrelevant. En contraire, it can differentiate between different types of road users (including pedestrians) and even inhabitants and other location-specific stakeholders.

Why do these works aim to shift the discussion's focus on individual motorized vehicles, then? While most fairness-related literature discourses vertical fairness in the context of transportation planning (how to balance different groups of road users, e.g., transit, individual motorized vehicles, and vulnerable road users), surprisingly few works address the work of horizontal fairness in the context of traffic engineering (how to balance similar individuals, such as individual motorized vehicles). We believe that shifting the focus on this important, yet neglected, perspective on fairness in transportation, we might enable greater, immediate real-world impact with overcoming the equity concerns impeding traffic demand management strategies such as congestion pricing. As the life reality in many countries, including the United States, Australia, and parts of Asia, is car-dependent, and walking or transit are not really viable options, these life realities require the kind of equity discussions we are suggesting to achieve an impact.

Applicability of the framework for differentiation: This framework can be used to specifically differentiate between different modes of transportation, categories of vehicles, types of users, regional and original differences, or purposes of travel. In many contexts, it can make sense to account for differences of road users due to the heterogeneity of the population.

Such a differentiation could be made by the normalization and weighting of the suggested, fairness-relevant resources. For instance, delay resources in the dianemetic case study: One could differentiate between different modes of transportation and prioritize the delays of transit vehicles by weighting their delays significantly higher than those of individual motorized vehicles. Or costs in the diorthotic case study: One could normalize the experienced costs by socio-economic aspects, such as the regional differences, income, gender, or age. Drivers that drive the longest distances for work purposes are usually those with the lowest income and might be those that should be least penalized by congestion pricing (depending on the fairness ideology at hand).

Last but not least, it is important to emphasize that this framework is a tool that can guide while assessing the fairness of and the development of more fair traffic engineering solutions, but it is not a traffic engineering solution. For example, one could explore how fair price differentiation is using the framework, but the framework itself is not suggesting price differentiation, as this would imply a specific fairness ideology already.

Equity-over-time and temporal fairness considerations: The framework presented in this paper evaluates distributive fairness over a defined observation horizon. This horizon may be a signal cycle, simulation episode, peak period, day, week, or longer policy period, depending on the traffic engineering problem and available data. Therefore, the framework is not inherently restricted to static fairness; the same metrics can be applied to cumulative delay, cumulative costs, cumulative exposure, or repeated access to scarce mobility resources over time. However, the present case studies focus on bounded simulation-based design problems and do not model longitudinal fairness across repeated interactions of the same individuals.

A full treatment of temporal fairness would require additional assumptions and data. In particular, individual-level temporal fairness requires the ability to identify recurring users and to track how delays, tolls, priority decisions, or denied access accumulate across multiple trips [5,101,102,117]. This is often not available in conventional traffic engineering systems and may introduce privacy and institutional constraints. In applications where individual identification is not feasible, temporal fairness can instead be approximated at an aggregated level; for example, by evaluating cumulative burdens for modes, vehicle classes, OD groups, districts, corridors, or affected resident groups over a day, week, or policy period. Such extensions are particularly relevant for behavioural control instruments such as pricing, rationing, and tradable mobility permits, where repeated participation and accumulated costs are central to perceived and distributive fairness.

Accounting for perceived fairness: It is also important to note that often, not only objective fairness, based on philosophical ideologies and reasoning, is what convinces in public discourses, but perceived fairness. Perceived fairness could, similar to differentiation, be achieved using weighting or normalizing. For instance, perceived delays or costs are often experienced non-linearly by individuals, where longer delays and higher costs are experienced disproportionally worse. Weighting delays and costs in such a non-linear way in the framework can better reflect the perceived fairness.

The presented framework focuses on objective distributive fairness and does not claim to fully model perceived fairness, which depends not only on distributive outcomes but also on expectations, transparency, procedural legitimacy, trust, information, and local social norms. Nevertheless, objective distributive metrics can provide an important basis for perceived fairness discussions because they make the consequences of traffic engineering decisions explicit and comparable.

Stakeholder conflicts and externalities: The present case studies focus primarily on road users and mode groups. This does not imply that the framework is limited to mobile users. In externality-related applications, the relevant fairness actors may be stationary or place-based stakeholders, such as residents, schools, retail shops, pedestrians, cyclists, or neighbourhoods affected by emissions, noise, safety risks, or reduced local accessibility. In such cases, fairness-relevant resources should be assigned to the groups that actually experience the burden: delays and travel costs to travellers, pollution and noise exposure to residents, and accessibility or loading impacts to local businesses.

Conflicts between stakeholder groups may be fundamentally incommensurable. For instance, reducing travel delays for drivers may increase emissions or noise exposure for residents along alternative routes. The proposed framework can make such conflicts explicit by computing separate fairness indicators for each stakeholder-resource pair, but it does not by itself determine the politically correct weighting between them. In practice, this weighting should be treated as a transparent policy choice, potentially supported by multi-criteria decision analysis, participatory planning, public consultation, or scenario-based sensitivity analysis. Thus, the framework provides the distributive diagnostic layer, while stakeholder deliberation or multi-criteria decision analysis can provide the decision-support layer for resolving conflicts between competing fairness claims.

Generalisability and practical application: The simulation-based case studies should be interpreted as proof-of-concept demonstrations rather than as directly generalisable empirical results. The specific numerical outcomes, optimal parameters, and magnitudes of the fairness-efficiency trade-offs depend on the assumed network topology, demand patterns, behavioural assumptions, controller type, and selected fairness metrics. Therefore, the results should not be transferred directly to other intersections, corridors, or pricing schemes without local calibration and validation. What is generalisable, however, is the proposed procedure for structuring a fairness discussion in traffic engineering: defining the traffic engineering problem, determining the transaction type, selecting relevant fairness ideologies, identifying affected users and resources, and choosing quantitative metrics for evaluation. In this sense, the case studies demonstrate how fairness considerations can be operationalised and compared with conventional efficiency objectives, rather than providing universal numerical recommendations.

Furthermore, the framework should be distinguished from the online control algorithm itself. Fairness metrics can be used offline to evaluate, compare, or calibrate candidate control strategies through microsimulation, sensitivity analysis, or digital-twin experiments. The real-time controller does not necessarily need to compute all fairness metrics online. For example, a max-pressure controller with pre-calibrated mode weights remains computationally simple during operation, while the fairness analysis is used to select or justify these weights before deployment. Computational tractability therefore depends on the chosen implementation: direct online optimization with complex fairness objectives may require additional algorithmic work, whereas simulation-based design and evaluation can be integrated into existing traffic engineering workflows.

7. Conclusions

This work highlighted the importance of fairness in road traffic engineering and advocated a new paradigm based on fairness rather than efficiency. The review of previous work on fair traffic engineering revealed that there is a lack of connection with the fairness literature, unsystematic discussion of fairness, and the employment of over-simplifying definitions of fairness. As a result, the necessity for a framework to assess fairness in a systematic way was identified. The study then proposed a distributive, quantitative, ideology-free, and pragmatic fairness framework for infrastructural and behavioural traffic control systems, which was showcased and demonstrated at the example of two case studies.

The case studies yielded valuable insights due to an integrated discussion of fairness from egalitarian, utilitarian, Rawlsian, Harsanyian, Aristotelian, and Luck-egalitarian schools of thought. The results described the nature of the relationship between fairness and efficiency, outlined fairness enhancements without efficiency losses, and revealed cluster-like patterns in various efficiency and fairness measures that reflect different fairness ideologies. The dianemetic case study highlighted how problematic a discussion based on egalitarianism, the most prevalent ideology in the transportation literature, can be, as it oversimplifies fairness elaborations and highly contradicts efficiency. The diorthotic case study demonstrated that static road pricing using economic instruments enhances fairness from all ideologies' point of view by allocating resources to those in the highest need. The multi-mode case study showcased the complexities when balancing different transportation modes.

Future work is encouraged to exploit this useful, quantitative framework when designing infrastructural and behavioural traffic engineering solutions and to address the need for an integrative, multi-perspective view on fairness. More extensive studies on the relationship of fairness and efficiency could quantitatively address different fairness ideologies. Studies on behavioural control could not only assess whether economic instruments are fair but also determine fairness-optimizing prices and explore fairness-optimizing price differentiation. In addition to that, intelligent transportation systems might leverage information on user heterogeneity and classification in order to account for differences between users to enhance fairness. Last but not least, the exploration of perceived fairness rather than objective fairness (e.g., perceived delays or costs instead of factual delays or costs) is a promising research direction.

Author Contributions: Conceptualization, K.R.; methodology, K.R.; software, K.R.; validation, K.R. and M.A.M.; formal analysis, K.R.; investigation, K.R.; resources, K.R.; data curation, K.R.; writing—original draft preparation, K.R.; writing—review and editing, M.A.M. and A.K.; visualization, K.R.; supervision, A.K. and M.A.M.; project administration, K.R.; funding acquisition, M.A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101203465 (project "FEDORA"), and from the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract No. REF-1131-52301. Furthermore, this work contributes to REproducible Research In Transportation Engineering (RERITE (https://www.rerite.org/)), advancing open science and transparency in transportation research, and the vision of a transportation community where open science, reproducible research and replicable studies are the norms, advancing scientific rigour, accelerating innovation and fostering translation into practice.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Code and data to reproduce the computational case studies will be provided on GitHub: https://github.com/DerKevinRiehl/fair_roads (accessed on 1 July 2025).

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Notes on Case Study Simulations

Appendix A.1. Simulation Environment

In the case studies, we employ the time-discrete micro-simulator SUMO [115]. For the simulation, we use SUMO's standard settings for vehicle. Each simulation consists of a tenminute simulation for transient response before the recording of 60 min of simulation starts. A time step size of one second was used. Various metrics are recorded during the recording. Vehicles are spawned with an exponential probability distribution ($\lambda = 5$).

Appendix A.2. Case Study: Signalized Intersection Management

Each simulation is repeated 10 times with different random seeds, and the average of the metrics is calculated in order to mitigate the random effects of the simulation. Both vehicle delay and vehicle delay per km travelled were investigated with similar results, which is why we chose to report vehicle delay per km results only.

Appendix A.3. Case Study: Static Road Pricing

Optimal road prices are determined assuming static flows. In various setups, we investigate the fairness measures and transportation efficiency for different splits. Each simulation consists of a 60 min simulation for transient response before the travel time of 200 vehicles for each route is recorded. The total flow is varied from 0 to 1100 vehicles per hour. We assume a VOT distribution to assess the fairness of different road prices. Numbers are based on the frequency distribution of the employees by wage level classes in 2018 by the Federal Statistical Office of Switzerland (https://www.bfs.admin.ch/asset/en/12488554, accessed on 27 February 2024). A simplifying assumption made here is that the VOT of the users refers to their salary levels. Exchange rate of 1 CHF = 1 € is assumed. More advanced VOT measures considering the urgency and travel purpose could be investigated in more advanced analyses.

Appendix B. Comments on Framework Design

- **Ideologies and Sufficientarianism:** Even though it enjoys popularity in Martens' transportation justice, we excluded Sufficientarianism from our discussion, as we aim to focus on objective, interpretation-free quantification of fairness. Sufficientarianism introduces the complexity of finding a sufficient minimum. Assuming a given sufficient minimum in a Sufficientarian sense, an inclusion into our framework could become possible.
- **Fairness-Relevant Resources and Available Alternatives:** One could argue that available alternatives are fairness-relevant, dianemetic resources in the context of behavioural control as well. Clearly, the availability of alternatives will determine the decision-making processes of individuals. However, the availability of alternatives, similar to available budgets, is usually determined by the socio-economic contexts of individuals, which is rather in the scope of long-term planning rather than short-term control. Therefore, we restrict our discussion at most to the redistribution of generated revenues to financial budgets. One could argue that on-demand transportation services could be affected by demand patterns on the short-term as well; in this case, we argue, they could be included in fairness-relevant discussions on traffic engineering. For example, modality choice: individuals could either drive by themselves, at the cost of delays, or some of them could switch to on-demand taxi services, at financial costs and potential waiting times if the demand exceeds the taxi-fleet's service capacity.

Appendix C. Quantitative Assessment of Fairness

Appendix C.1. Dispersion and Concentration Metrics

Dispersion metrics aim to measure the inequality of a given distribution across a population with n individuals, where x_i is the amount of individual $i = 1 \ldots n$, and $\overline{x}$ represents the population average amount. The most common representative is the standard deviation. Various concentration ratios have been proposed as dispersion metrics in the economic literature [118], many of them being familiar with Shannon's entropy [119]. The Lorenz Curve [120] $L(x)$ is a common, economic tool to analyse the inequality of distributions and depicted in Figure A1; concentration ratios and thus dispersion metrics can be considered as asymmetry measures of the Lorenz Curve.

In Table A1, we present the most common dispersion metrics. The first four metrics range from 0 (perfect equality) to 1 (perfect inequality), while the lower four lack an upper bound. The Gini-coefficient is the most widely used dispersion metric in the economic literature. The Atkinson-index offers the possibility to weight values in order to express the level of inequality aversion (larger ϵ means higher aversion) and to control the sensitivity of the index towards inequality. The Theil-index [121] is particularly useful, as it is decomposable in order to analyse which groups contribute most to the total inequality. The Palma-index [122] distinguishes itself from the other measures as being comparative by analysing the ratio of specific groups at the top and bottom of the distribution.

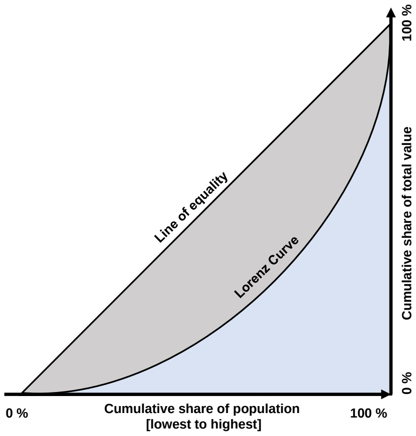

Figure A1. Lorenz Curve. The Lorenz Curve is a tool to assess the equality of a distribution. The curve is constructed as follows: the values of the population are sorted in ascending order and then plotted by cumulative share of population over cumulative share of total value. In a perfectly equal distribution, the Lorenz curve would equal a diagonal; in a perfectly unequal distribution, it would equal a jump to the top on the very right of the diagram.

Table A1. Dispersion & Concentration Metrics. Statistical dispersion and economic concentration metrics are used to assess the equality of distributions. The formulas cover the most important measures and are denoted to determine the equality of a distribution of n values x_i, where $\bar{x}$ represents the average over all x_i.

Metric	Formula
Atkinson-Index [123]	$A_\epsilon = \begin{cases} 1 - \frac{1}{\bar{x}}(\frac{1}{n}\sum_{i=1}^{n} x_i^{1-\epsilon})^{1/(1-\epsilon)} \\ for\ 0 \leq \epsilon < 1 \\ 1 - \frac{1}{\bar{x}}(\Pi_{i=1}^{n} x_i)^{1/N} \\ for\ 0 \leq \epsilon < 1 \\ 1 - \frac{1}{\bar{x}}\ \min_i(x_i) \\ for\ \epsilon = +\infty \end{cases}$

Table A1. *Cont.*

Metric	Formula
Gini-Coefficient [111]	$G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\|x_i - x_j\|}{2n\sum_{i=1}^{n}x_i}$
Herfindahl-Index [124]	$HH_n = \frac{HH - \frac{1}{n}}{1 - \frac{1}{n}}, HH = \sum_{i=1}^{n}(\frac{x_i}{\sum_{j=1}^{n}x_j})^2$
Hirschmann-Index Hoover-Index [125]	$H = \frac{1}{2}\frac{\sum_i^n \|x_i - \overline{x}\|}{\sum_i^n x_i}$
Palma-Index [122]	$P = \frac{\int_{0\%}^{40\%} L(x)dx}{\int_{90\%}^{100\%} L(x)dx}$
Standard Deviation	$\sigma = \frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2$
Theil-Index T [121]	$T_T = \frac{1}{n}\sum_{i=1}^{n}\frac{x_i}{\overline{x}}ln(\frac{x_i}{\overline{x}})$
Theil-Index L [121]	$T_L = \frac{1}{n}\sum_{i=1}^{n}ln(\frac{\overline{x}}{x_i})$

Appendix C.2. Welfare Economics

Welfare economics is a discipline in economics that applies micro-economic techniques with the ultimate goal of analysing how resource allocation affects societal welfare. It develops and suggests tools to improve and ideally maximize welfare. Resource allocation determines the economic welfare of a society and is a result of economic processes, such as markets. The two fundamental theorems of welfare economics state conditions under which competitive market processes achieve (i) economically optimal allocations and (ii) that these are achieved at market equilibrium states. Pareto-optimality is one of the most recognized optimality measures in economics; it describes that a deviation from the optimal resource allocation cannot improve any individual's situation without worsening another's. Markets can reach equilibrium states, in which no agent has any incentive to change its behaviour (for a period of time without disturbance). The assumptions of the fundamental theorems of welfare economics are restrictive and describe idealized markets that can hardly be found in practice. Phenomena such as strong inequality, externalities, public goods, high volatility, non-satiation, irrationality of consumers and firms, and economies of scale (non-convexity production sets) defect markets. Therefore, welfare economics developed and advocated a tool-set of policy instruments to cope with the defects of markets.

Pareto-optimal equilibria are economically feasible, but that does not imply they are socially feasible, desirable, or fair. Welfare economics applies social welfare functions to rank allocations at the Pareto-optimal front in order to determine the most desirable (welfare-maximizing) solution(s). Allocations of equal social welfare function values form social indifference curves. Figure A3 shows how social welfare maximization can be achieved at the tangential point of bliss between the Pareto-optimal front and a social indifference curve. The choice of such a welfare function depends on many factors, including economic efficiency, equity (fairness), and freedom. In theory, maximization of welfare can be achieved by governmental intervention into markets aiming to transfer the market equilibrium along the Pareto-optimal frontier to the point of bliss, using instruments such as taxation, subsidisation, or redistribution (see Figure A3). Depending on the shape of the social indifference curve, the point of bliss can also be a tangential area of bliss.

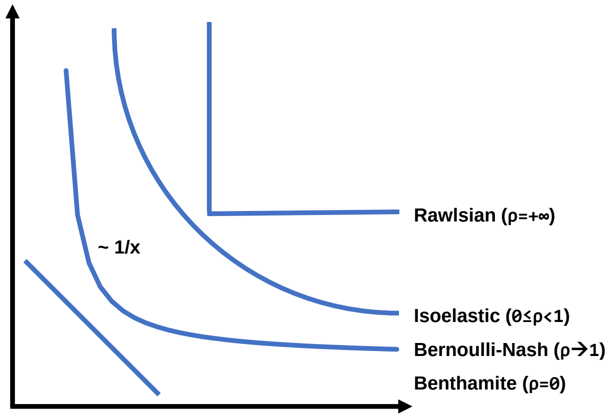

Figure A2. Bergson-Samuelson Welfare Functions. The Bergson-Samuelson family of welfare functions are described one formula, the Bergson-Samuelson welfare function, with a specific parameter p that can be tuned to match many of the other welfare functions, including Rawlsian, Isoelastic, Bernoulli-Nash and Benthamite welfare functions.

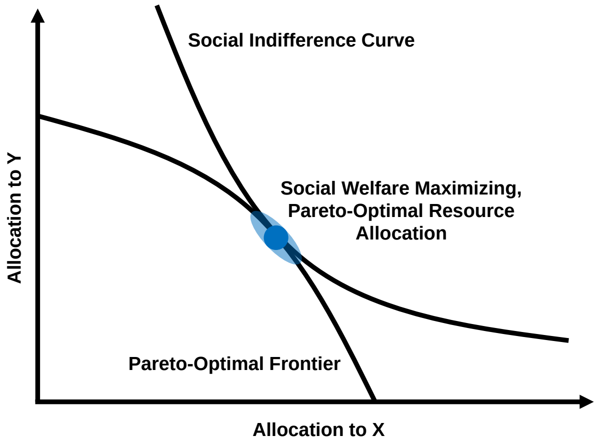

Figure A3. Welfare Maximization. Pareto-optimal resource allocations are described by the Pareto-Optimal Frontier. Social welfare function and Pareto-optimal frontier skirt at the point of bliss, which is where social welfare is maximized given the Pareto-optimality restriction. The point of bliss can also be an area of bliss.

Appendix C.3. Welfare Functions

Welfare functions are a formal representation of individual notions of welfare aggregated on a societal level. Individuals have an individual income y_i that they can use to trade on markets and get resources x_i allocated as a result. These resources generate a certain utility u_i for the individual. On a societal level, the market transaction process determines a resource allocation x. Leontief-Lerner welfare functions describe welfare as a function of available resources. Bergson-Samuelson welfare functions describe welfare as a function of individual utilities. Capability-approach welfare functions describe welfare as a function of incomes.

Table A2 shows different formalizations of the three presented groups of welfare functions. The isoelastic welfare function is a general formalization of the Bergson–Samuelson welfare function displayed in Figure A2, with the possibility to weight each individual's utility with α_i; for $\rho = 0$, it becomes the Benthamite welfare function in the sense of utilitarian fairness; for $\rho = +\infty$, it becomes the Rawlsian welfare function in the sense of the Rawlsian fairness; for $\rho \to 1$, it becomes the Bernoulli-Nash welfare function; for any other ρ, it is an intermediate welfare function between the extremes of utilitarian and Rawlsian fairness. Sen and Foster apply dispersion metrics such as the Gini-Coefficient G and the Theil-index T_T.

While incomes y_i and allocated resources x_i are easy to measure, Bergson–Samuelson welfare functions are complex in that they require knowledge or estimations of individual functions $f_i(x) = u_i$ that translate allocated resources to utilities. Therefore, several of the Bergson–Samuelson welfare functions are used with incomes y_i instead of utilities u_i in modern welfare economic applications for simplicity. An important assumption made doing so is that individuals can generate equal utilities from the same amount of income no matter what resources they buy as consumers. Following the capability approach, subsidising measures can help to relax this assumption and support disabled people that need more resources to achieve the same utility as not disabled people.

Table A2. Welfare Functions. Social welfare functions aim to define the social welfare W of resource allocations, where x describes the input to the resource allocation process (e.g., financial wealth), y describes the output of the resource allocation process (e.g., allocated resources), and u describes the utility of the allocated resources to the individuals. There are three types of welfare functions: Leontief–Lerner, Bergson–Samuelson, and Capability approach welfare functions.

Title	Formalization
Leontief-Lerner	$W = F(x_1, \ldots, x_n)$
Bergson-Samuelson	$W = F(u_1, \ldots, u_n)$
Isoelastic	$W = \frac{1}{1-\rho} \sum_{i=1}^{n} \alpha_i u_i^{1-\rho}$
Benthamite	$W = \sum_{i=1}^{n} u_i$
Rawlsian	$W = \min_{i=1}^{n} u_i$
Bernoulli-Nash	$W = \Pi_{i=1}^{n} \alpha_i u_i$
Capability-approach	$W = F(y_1, \ldots, y_n)$
Sen	$W = \overline{y}(1 - G)$
Foster	$W = \overline{y} e^{-T_T}$

Appendix D. Fairness Definitions

Table A3. Fairness Ideologies. In the history of philosophy, many schools, respectively, ideologies have emerged when discoursing the topic of fairness. The table summarizes the most important ideologies, their underlying guiding principles, and most notable influencers (authors).

Ideology	Guiding Principle	Influencers
Aristocratic	Advocate inequalities in distribution, but equality in proportions of resource provision and social status or contribution.	Aristotle
Communitarist	Fairness concept is only possible for a culturally-homogeneous community. Rejection of a universalist theory, advocation of a context-specific theory.	Alasdair MacIntyre, Michael Sandel, Charles Taylor, Michael Walzer
Cosmopolitan	All individuals need to be considered (despite nationality, race, gender, ...).	Simon Caney
Capability Approach	Rather than focus on the equal rights for a dignified life, focus on the equal abilities to achieve a dignified life.	Amartya Sen, Martha Nussbaum
Discourse-ethic	Fairness as part of moral and ethical behavior determined via self-reflection and discussions.	Jürgen Habermas, Karl-Otto Apel
Egalitarian	Focus on natural law, equality of humans implies pure equality is fair.	Jean-Jacques Rousseau, Thomas Nagel

Table A3. *Cont.*

Ideology	Guiding Principle	Influencers
Harsanyian	Similar to Rawlsian, but with focus on best average situation.	John Harsanyi
Hedonistic	Theory of a good life by maximizing desire and enjoyment of life.	Epikur
Intuitionism	Particular distributive problems must be discussed to particular cases.	Brian Barry, David Miller
Kantian	Categorial imperative, universalistic maxims must base on human ratio.	Immanuel Kant
Liberal	Focus on as few government and legislation as necessary, focus on property rights, liberty, free markets, no redistribution.	John Locke
Libertarian	Sceptic view on governments and legislation, focus on individual and free markets.	Robert Nozick
Luck-egalitarian	Acknowledge that person's skills and abilities are not equal, therefore governmental intervention to compensate for undeserved misfortune complements the power of markets.	Ronald Dworkin, Richard Arneson, Gerald Cohen
Marxist/Frankfurt School	Critical view on theory of fairness as an instrument of elites to suppress populations.	Karl Marx, Max Horkheimer, Theodor W. Adorno, Walter Benjamin
Nietzschean	Fairness is the enemy of freedom.	Friedrich Nietzsche
Rawlsian	Universalist fairness concept based on reason and freedom, focus on best situation for least-advantaged.	John Rawls
Social, Socialist, Social democratic	Intervention into free markets to ensure minimum for every one and improve equality of chances, focus on economics rather than politics, emphasis on equality.	Thomas Müntzer, William Thompson, Charles Fourier, Wiliam Godwin, August Bebel
Sufficientarian	Rather than having the same, focus on having enough.	John Roemer, Harry Frankfurt
Utilitarian	Focus on social welfare and the greater good, societal utility maximization as the main goal.	Jeremy Bentham, John Stuart Mill
Virtuous/Deuterocanonic	Desirable behaviour and character trait of individual or deity	Aischylos

References

1. Karner, A.; Bills, T.; Golub, A. Emerging perspectives on transportation justice. *Transp. Res. Part D Transp. Environ.* **2023**, *116*, 103618. [CrossRef]
2. Saeidizand, P.; Fransen, K.; Boussauw, K. Revisiting car dependency: A worldwide analysis of car travel in global metropolitan areas. *Cities* **2022**, *120*, 103467. [CrossRef]
3. Verhoef, E. The economics of traffic congestion. In *The Economics of Traffic Congestion*; Edward Elgar Publishing Limited: Cheltenham, UK, 2010. [CrossRef]
4. Roess, R.P.; Prassas, E.S.; McShane, W.R. *Traffic Engineering*; Pearson/Prentice Hall: Hoboken, NJ, USA, 2004.
5. Provoost, J.; Cats, O.; Hoogendoorn, S. Design and classification of tradable mobility credit schemes. *Transp. Policy* **2023**, *136*, 59–69. [CrossRef]
6. Varian, H.R. Fairness. In *The New Palgrave Dictionary of Economics*; Palgrave Macmillan UK: London, UK, 2018; pp. 4411–4413. [CrossRef] [PubMed]

7. Yin, Y.; Liu, H.; Benouar, H. A note on equity of ramp metering. In *Proceedings of the 7th International IEEE Conference on Intelligent Transportation Systems (IEEE Cat. No. 04TH8749)*; IEEE: Piscataway, NJ, USA, 2004; pp. 497–502. [CrossRef]
8. Li, D.; Ranjitkar, P.; Zhao, Y. Efficiency and equity performance of a coordinated ramp metering algorithm. *Promet-Traffic Transp.* **2016**, *28*, 507–515. [CrossRef]
9. Aboudolas, K.; Geroliminis, N. Perimeter and boundary flow control in multi-reservoir heterogeneous networks. *Transp. Res. Part B Methodol.* **2013**, *55*, 265–281. [CrossRef]
10. Eliasson, J. Is congestion pricing fair? Consumer and citizen perspectives on equity effects. *Transp. Policy* **2016**, *52*, 1–15. [CrossRef]
11. Van den Berghe, W. The Influence of Fairness and Ethical Trade-Offs on Public Support for Road Safety Measures: An International and Intercultural Exploration. Ph.D. Thesis, University of London, University College London, London, UK, 2022.
12. De Palma, A.; Lindsey, R.; Quinet, E.; Vickerman, R. *A Handbook of Transport Economics*; Edward Elgar Publishing: Cheltenham, UK, 2011; ISBN 978-1-78347-285-7.
13. Goodwin, P.B. Solving congestion (when we must not build roads, increase spending, lose votes, damage the economy or harm the environment, and will never find equilibrium). In *Inaugural Lecture for the Professorship of Transport Policy University College London*; University College London (UCL): London, UK, 1997.
14. Martens, K.; Golub, A.; Robinson, G. A justice-theoretic approach to the distribution of transportation benefits: Implications for transportation planning practice in the United States. *Transp. Res. Part A Policy Pract.* **2012**, *46*, 684–695. [CrossRef]
15. Inwood, J.F.; Alderman, D.; Williams, J. 'Where Do We Go From Here?' Transportation Justice and the Struggle for Equal Access. *Southeast. Geogr.* **2015**, *55*, 417–433. [CrossRef]
16. Hendriks, O. Equity in Traffic Light Control: Identifying-and Measuring Equity Traffic Light Control. A Case Study to Improve Equity at the Intersection A050 in Deventer for Intelligent Traffic Light Controller: Flowtack. Master's Thesis, TU Delft, Delft, The Netherlands, 2021.
17. Wissema, H. Driving through red lights: How warning signals are missed or ignored. *Long Range Plan.* **2002**, *35*, 521–539. [CrossRef]
18. Huntley, S. Why so many people ignore traffic laws. In *Transportation Research Records*; National Academies of Sciences, Engineering, and Medicine: Washington, DC, USA, 1983.
19. Jusoh, R.M.; Ampountolas, K. Distributed perimeter flow control of transport networks. In *Proceedings of the 49th Annual UTSG Conference*; UTSG: Scarborough, ON, Canada, 2017.
20. Gurney, G.G.; Mangubhai, S.; Fox, M.; Kim, M.K.; Agrawal, A. Equity in environmental governance: Perceived fairness of distributional justice principles in marine co-management. *Environ. Sci. Policy* **2021**, *124*, 23–32. [CrossRef]
21. Jackson, B.; Kubzansky, L.D.; Wright, R.J. Linking perceived unfairness to physical health: The perceived unfairness model. *Rev. Gen. Psychol.* **2006**, *10*, 21–40. [CrossRef]
22. Pereira, R.H.; Schwanen, T.; Banister, D. Distributive justice and equity in transportation. *Transp. Rev.* **2017**, *37*, 170–191. [CrossRef]
23. Golub, A.; Martens, K. Using principles of justice to assess the modal equity of regional transportation plans. *J. Transp. Geogr.* **2014**, *41*, 10–20. [CrossRef]
24. Bang, H.; Dave, A.; Tzortzoglou, F.N.; Wang, S.; Malikopoulos, A.A. On mobility equity and the promise of emerging transportation systems. *IEEE Trans. Intell. Transp. Syst.* **2025**, *26*, 10623–10637. [CrossRef]
25. Yan, S.; Zhang, J.; Büscher, D.; Burgard, W. Efficiency and equity are both essential: A generalized traffic signal controller with deep reinforcement learning. In *Proceedings of the 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*; IEEE: Piscataway, NJ, USA, 2020; pp. 5526–5533. [CrossRef]
26. Shirasaka, S.; Kodama, N.; Harada, T. Distributed Traffic Signal Control with Fairness Using Deep Reinforcement Learning. In *Proceedings of the 2023 SICE International Symposium on Control Systems (SICE ISCS)*; IEEE: Piscataway, NJ, USA, 2023; pp. 117–122. [CrossRef]
27. Raeis, M.; Leon-Garcia, A. A deep reinforcement learning approach for fair traffic signal control. In *Proceedings of the 2021 IEEE International Intelligent Transportation Systems Conference (ITSC)*; IEEE: Piscataway, NJ, USA, 2021; pp. 2512–2518. [CrossRef]
28. Li, H. Equity and real-time traffic signal scheduling algorithm. *J. Comput. Appl.* **2012**, *32*, 1161. [CrossRef]
29. Huang, X.; Wu, D.; Boulet, B. Fairness-Aware Model-Based Multi-Agent Reinforcement Learning for Traffic Signal Control. In *International Conference of Learning Representations (ICLR)*; Curran Associates, Inc.: Red Hook, NY, USA, 2023.
30. Meng, Q.; Khoo, H.L. A Pareto-optimization approach for a fair ramp metering. *Transp. Res. Part C Emerg. Technol.* **2010**, *18*, 489–506. [CrossRef]
31. Amini, N.; Gardner, L.; Waller, S.T. New horizontal equity measure for ramp meters. *Transp. Res. Rec.* **2016**, *2568*, 90–102. [CrossRef]
32. Kotsialos, A.; Papageorgiou, M. Efficiency versus fairness in network-wide ramp metering. In *Proceedings of the ITSC 2001. 2001 IEEE Intelligent Transportation Systems (Cat. No. 01TH8585)*; IEEE: Piscataway, NJ, USA, 2001; pp. 1189–1194. [CrossRef]

33. Kesten, A.S.; Ergün, M.; Yai, T. An analysis on efficiency and equity of fixed-time ramp metering. *J. Transp. Technol.* **2013**, *3*, 48–56. [CrossRef]
34. Lu, C.; Huang, J.; Deng, L.; Gong, J. Coordinated ramp metering with equity consideration using reinforcement learning. *J. Transp. Eng. Part A Syst.* **2017**, *143*, 04017028. [CrossRef]
35. Levinson, D.M.; Zhang, L.; Sheikh, A. *Measuring the Equity and Efficiency of Ramp Meters*; Center for Transportation Studies, University of Minnesota: Minneapolis, MN, USA, 2004.
36. Moshahedi, N.; Kattan, L. Alpha-fair large-scale urban network control: A perimeter control based on a macroscopic fundamental diagram. *Transp. Res. Part C Emerg. Technol.* **2023**, *146*, 103961. [CrossRef]
37. Riehl, K.; Kouvelas, A.; Makridis, M.A. Quantitative fairness—A framework for the design of equitable cybernetic societies. *Comput. Hum. Behav. Artif. Hum.* **2025**, 6, 100236. [CrossRef]
38. Waller, S.T.; Polydoropoulou, A.; Tassiulas, L.; Ziliaskopoulos, A.; Jian, S.; Wagenknecht, S.; Hirte, G.; Ukkusuri, S.; Ramadurai, G.; Bednarz, T. Mobility as a Resource (MaaR) for resilient human-centric automation—A vision paper. *Data Sci. Transp.* **2025**, *7*, 1. [CrossRef]
39. Rawls, J. *A Theory of Justice*; Harvard University Press: London, UK, 1971. [CrossRef]
40. Walzer, M. *Spheres of Justice: A Defense of Pluralism and Equality*; Basic Books: New York, NY, USA, 1983.
41. Nussbaum, M.C. *Creating Capabilities: The Human Development Approach*; Harvard University Press: London, UK, 2011. Available online: https://www.hup.harvard.edu/books/9780674072350 (accessed on 1 July 2026).
42. Sen, A. The idea of justice. *J. Hum. Dev.* **2008**, *9*, 331–342. [CrossRef]
43. Wolf, U. *Aristoteles' "Nikomachische Ethik"*; Wissenschaftliche Buchgesellschaft Darmstadt: Darmstadt, Germany, 2002.
44. Goppel, A.; Mieth, C.; Neuhäuser, C. *Handbuch Gerechtigkeit*; Springer: Berlin/Heidelberg, Germany, 2016; ISBN 978-3-476-02463-3. [CrossRef]
45. Hume, D. *A Treatise of Human Nature: Being an Attempt to Introduce the Experimental Method of Reasoning into Moral Subjects*; Thomas Longman: London, UK, 1740.
46. Carter, G.G.; Wilkinson, G.S. Social benefits of non-kin food sharing by female vampire bats. *Proc. R. Soc. B Biol. Sci.* **2015**, *282*, 20152524. [CrossRef] [PubMed]
47. Brosnan, S.F.; de Waal, F.B. Evolution of responses to (un) fairness. *Science* **2014**, *346*, 1251776. [CrossRef] [PubMed]
48. Corradi-Dell'Acqua, C.; Tusche, A.; Vuilleumier, P.; Singer, T. Cross-modal representations of first-hand and vicarious pain, disgust and fairness in insular and cingulate cortex. *Nat. Commun.* **2016**, *7*, 10904. [CrossRef] [PubMed]
49. De Cremer, D.; Brockner, J.; Fishman, A.; van Dijke, M.; van Olffen, W.; Mayer, D.M. When do procedural fairness and outcome fairness interact to influence employees' work attitudes and behaviors? The moderating effect of uncertainty. *J. Appl. Psychol.* **2010**, *95*, 291. [CrossRef] [PubMed]
50. Hitti, A.; Mulvey, K.L.; Killen, M. Social exclusion and culture: The role of group norms, group identity and fairness. *An. Psicol.* **2011**, *27*, 587–599.
51. Kozlowski, S.W.; Klein, K.J. A multilevel approach to theory and research in organizations: Contextual, temporal, and emergent processes. In *Multilevel Theory, Research and Methods in Organizations: Foundations, Extensions, and New Directions*; Jossey-Bass: San Francisco, CA, USA, 2000; pp. 3–90.
52. Martens, K. *Transport Justice: Designing Fair Transportation Systems*; Routledge: Abingdon, UK, 2016; ISBN 9780415638326. [CrossRef]
53. Sanchez, T.W.; Schweitzer, L. *Assessing Federal Employment Accessibility Policy: An Analysis of the JARC Program*; Brookings Institution: Washington, DC, USA, 2008.
54. Hananel, R.; Berechman, J. Justice and transportation decision-making: The capabilities approach. *Transp. Policy* **2016**, *49*, 78–85. [CrossRef]
55. Vanoutrive, T.; Cooper, E. How just is transportation justice theory? The issues of paternalism and production. *Transp. Res. Part A Policy Pract.* **2019**, *122*, 112–119. [CrossRef]
56. Karner, A.; Duckworth, R. 'Pray for transit': Seeking transportation justice in metropolitan Atlanta. *Urban Stud.* **2019**, *56*, 1882–1900. [CrossRef]
57. Johansen, N.; Wilson, R.; Tichon, J.; Senserrick, T.; Tranter, K. Decolonizing road safety for transportation justice in Australia. *Transp. Res. Part D Transp. Environ.* **2021**, *98*, 102970. [CrossRef]
58. Blumenberg, E. Social equity and urban transportation. In *The Geography of Urban Transportation*; The Guilford Press: Guilford, NY, USA, 2017; Volume 332, ISBN 9781462529650.
59. Karner, A.; London, J.; Rowangould, D.; Manaugh, K. From transportation equity to transportation justice: Within, through, and beyond the state. *J. Plan. Lit.* **2020**, *35*, 440–459. [CrossRef]
60. Ballo, L.; de Freitas, L.M.; Meister, A.; Axhausen, K.W. The E-Bike City as a radical shift toward zero-emission transport: Sustainable? Equitable? Desirable? *J. Transp. Geogr.* **2023**, *111*, 103663. [CrossRef]

61. Karner, A. Planning for transportation equity in small regions: Towards meaningful performance assessment. *Transp. Policy* **2016**, *52*, 46–54. [CrossRef]
62. Shoup, D. *High Cost of Free Parking*; Routledge: Abingdon, UK, 2021; ISBN 978-1932364965.
63. Hansmann, K.J.; Razon, N. Transportation Justice and Health. *Milbank Q.* **2023**, *102*, 11–27. [CrossRef] [PubMed]
64. Forkenbrock, D.J.; Schweitzer, L.A. Environmental justice in transportation planning. *J. Am. Plan. Assoc.* **1999**, *65*, 96–112. [CrossRef]
65. Shields, L. The prospects for sufficientarianism. *Utilitas* **2012**, *24*, 101–117. [CrossRef]
66. Bills, T.S.; Twumasi-Boakye, R.; Broaddus, A.; Fishelson, J. Towards transit equity in Detroit: An assessment of microtransit and its impact on employment accessibility. *Transp. Res. Part D Transp. Environ.* **2022**, *109*, 103341. [CrossRef]
67. Desjardins, E.; Higgins, C.D.; Paez, A. Examining equity in accessibility to bike share: A balanced floating catchment area approach. *Transp. Res. Part D Transp. Environ.* **2022**, *102*, 103091. [CrossRef]
68. Figliozzi, M.; Unnikrishnan, A. Home-deliveries before-during COVID-19 lockdown: Accessibility, environmental justice, equity, and policy implications. *Transp. Res. Part D Transp. Environ.* **2021**, *93*, 102760. [CrossRef] [PubMed]
69. Calafiore, A.; Dunning, R.; Nurse, A.; Singleton, A. The 20-minute city: An equity analysis of Liverpool City Region. *Transp. Res. Part D Transp. Environ.* **2022**, *102*, 103111. [CrossRef]
70. Jusoh, R.M.; Ampountolas, K. Multi-gated perimeter flow control of transport networks. In *Proceedings of the 2017 25th Mediterranean Conference on Control and Automation (MED)*; IEEE: Piscataway, NJ, USA, 2017; pp. 731–736. [CrossRef]
71. Kotsialos, A.; Papageorgiou, M.; Middelham, F. Optimal coordinated ramp metering with advanced motorway optimal control. *Transp. Res. Rec.* **2001**, *1748*, 55–65. [CrossRef]
72. Zhang, L.; Levinson, D. Optimal freeway ramp control without origin–destination information. *Transp. Res. Part B Methodol.* **2004**, *38*, 869–887. [CrossRef]
73. Zhang, H.; Shen, W. Access control policies without inside queues: Their properties and public policy implications. *Transp. Res. Part B Methodol.* **2010**, *44*, 1132–1147. [CrossRef]
74. Jain, R. *The Art of Computer Systems Performance Analysis: Techniques for Experimental Design, Measurement, Simulation, and Modeling*; Wiley: New York, NY, USA, 1991; Volume 1, ISBN 978-0471503361.
75. Levinson, D.; Zhang, L. Ramp meters on trial: Evidence from the Twin Cities metering holiday. *Transp. Res. Part A Policy Pract.* **2006**, *40*, 810–828. [CrossRef]
76. Khele, A.; Jiang, C.; Wang, H. Fairness-aware optimization of vehicle-to-vehicle interaction for smart EV charging coordination. In *Proceedings of the 2023 IEEE/IAS 59th Industrial and Commercial Power Systems Technical Conference (I&CPS)*; IEEE: Piscataway, NJ, USA, 2023; pp. 1–9. [CrossRef]
77. Bang, H.; Dave, A.; Tzortzoglou, F.N.; Malikopoulos, A.A. A mobility equity metric for multi-modal intelligent transportation systems. *IFAC-PapersOnLine* **2024**, *58*, 114–119. [CrossRef]
78. Li, S.; Robusté, F. From urban congestion pricing to tradable mobility credits: A review. *Transp. Res. Procedia* **2021**, *58*, 670–677. [CrossRef]
79. Luo, M.; Ma, Z.; Zhao, W.; Enoch, M.; Steven, I.; Chien, J. An ex-post evaluation of the public acceptance of a license plate-based restriction policy: A case study of Xi'an, China. *Transp. Res. Part A Policy Pract.* **2022**, *155*, 259–282. [CrossRef]
80. Yu, D.P.; Li, Z.C. Income distribution, implementation sequence, and equity in auto ownership rationing. *Transp. Res. Part B Methodol.* **2023**, *173*, 59–89. [CrossRef]
81. Taylor, B.D.; Kalauskas, R. Addressing equity in political debates over road pricing: Lessons from recent projects. *Transp. Res. Rec.* **2010**, *2187*, 44–52. [CrossRef]
82. Dogterom, N.; Bao, Y.; Xu, M.; Ettema, D. Acceptability of a tradable driving credit scheme in the Netherlands and Beijing. *Case Stud. Transp. Policy* **2018**, *6*, 499–509. [CrossRef]
83. Finkleman, J.; Casello, J.; Fu, L. Empirical evidence from the Greater Toronto Area on the acceptability and impacts of HOT lanes. *Transp. Policy* **2011**, *18*, 814–824. [CrossRef]
84. Fan, W.; Jiang, X. Tradable mobility permits in roadway capacity allocation: Review and appraisal. *Transp. Policy* **2013**, *30*, 132–142. [CrossRef]
85. Bogenberger, K.; Blum, P.; Dandl, F.; Hamm, L.S.; Loder, A.; Malcolm, P.; Margreiter, M.; Sautter, N. MobilityCoins—A new currency for the multimodal urban transportation system. *arXiv* **2021**, arXiv:2107.13441. [CrossRef]
86. Chen, D.; Sun, Y.; Yang, Z. Optimization of the travel ban scheme of cars based on the spatial distribution of the last digit of license plates. *Transp. Policy* **2020**, *94*, 43–53. [CrossRef]
87. Li, X.; Yang, H.; Ke, J. Booking cum rationing strategy for equitable travel demand management in road networks. *Transp. Res. Part B Methodol.* **2023**, *167*, 261–274. [CrossRef]
88. Daljord, Ø.; Pouliot, G.; Xiao, J.; Hu, M. The black market for beijing license plates. *arXiv* **2021**, arXiv:2105.00517. [CrossRef]
89. Wang, S.; Zhao, J. The distributional effects of lotteries and auctions—License plate regulations in Guangzhou. *Transp. Res. Part A Policy Pract.* **2017**, *106*, 473–483. [CrossRef]

90. Weinstein, A.; Sciara, G.C. Assessing the Equity Implications of HOT Lanes ; A Report Prepared for the Santa Clara Valley Transportation Authority. 2004. Available online: https://www.academia.edu/download/30834231/hot_equity.pdf (accessed on 1 July 2026).
91. Coyle, D.J. "This Land is Your Land, This Land is My Land": Cultural Conflict in Environmental and Land-Use Regulation. In *Politics, Policy, and Culture*; Routledge: Abingdon, UK, 2019; pp. 33–50. ISBN 9780429302503. . [CrossRef]
92. Abulibdeh, A. Implementing congestion pricing policies in a MENA Region City: Analysis of the impact on travel behaviour and equity. *Cities* **2018**, *74*, 196–207. [CrossRef]
93. Schweitzer, L.; Taylor, B.D. Just road pricing. *ACCESS Mag.* **2010**, *1*, 2–7.
94. Karlström, A.; Franklin, J.P. Behavioral adjustments and equity effects of congestion pricing: Analysis of morning commutes during the Stockholm Trial. *Transp. Res. Part A Policy Pract.* **2009**, *43*, 283–296. [CrossRef]
95. Zhicai, J.; Qingyu, L.; Zhongning, F.; Hongfei, J. Equity effects of congestion pricing on urban road resources allocation. *J. Transp. Syst. Eng. Inf. Technol.* **2008**, *8*, 74–79. [CrossRef]
96. Eliasson, J.; Mattsson, L.G. Equity effects of congestion pricing: Quantitative methodology and a case study for Stockholm. *Transp. Res. Part A Policy Pract.* **2006**, *40*, 602–620. [CrossRef]
97. Maheshwari, C.; Kulkarni, K.; Pai, D.; Yang, J.; Wu, M.; Sastry, S. Congestion Pricing for Efficiency and Equity: Theory and Applications to the San Francisco Bay Area. *arXiv* **2024**, arXiv:2401.16844. [CrossRef]
98. Ecola, L.; Light, T. *Equity and Congestion Pricing*; Rand Corporation: Santa Monica, CA, USA, 2009; pp. 1–45.
99. Manville, M.; Goldman, E. Would congestion pricing harm the poor? Do free roads help the poor? *J. Plan. Educ. Res.* **2018**, *38*, 329–344. [CrossRef]
100. Manville, M. Longer View: The Fairness of Congestion Pricing. *Transf. Mag.* **2019**, *3*. Available online: https://transfersmagazine.org/magazine-article/issue-3/longer-view-the-fairness-of-congestion-pricing/ (accessed on 1 July 2025).
101. Riehl, K.; Kouvelas, A.; Makridis, M.A. Karma economies for sustainable urban mobility—A fair approach to public good value pricing. *npj Sustain. Mobil. Transp.* **2024**, *1*, 14. [CrossRef]
102. Riehl, K.; Kouvelas, A.; Makridis, M.A. Resource Allocation with Karma Mechanisms—A Review. *Economies* **2024**, *12*, 211. [CrossRef]
103. Elokda, E.; Bolognani, S.; Censi, A.; Dörfler, F.; Frazzoli, E. A self-contained karma economy for the dynamic allocation of common resources. *Dyn. Games Appl.* **2024**, *14*, 578–610. [CrossRef]
104. Elokda, E.; Cenedese, C.; Zhang, K.; Censi, A.; Lygeros, J.; Frazzoli, E.; Dörfler, F. CARMA: Fair and Efficient Bottleneck Congestion Management via Nontradable Karma Credits. *Transp. Sci.* **2024**, *59*, 207–450. [CrossRef]
105. Servatius, P.; Hamm, L.; Loder, A.; Bogenberger, K. Conceptualizing an individual full-trip tradable credit scheme for multi-modal demand and supply management: The MobilityCoin System. *Front. Future Transp.* **2022**, *3*, 914496. [CrossRef]
106. Mill, J.S. Utilitarianism. In *Seven Masterpieces of Philosophy*; Routledge: Abingdon, UK, 2016; pp. 329–375. [CrossRef]
107. Harsanyi, J.C. Can the maximin principle serve as a basis for morality? A critique of John Rawls's theory. *Am. Political Sci. Rev.* **1975**, *69*, 594–606. [CrossRef]
108. Dworkin, R. What is equality? Part 1: Equality of welfare. *Philos. Public Aff.* **1981**, *10*, 185–246.
109. Dworkin, R. *Sovereign Virtue: The Theory and Practice of Equality*; Harvard University Press: London, UK, 2000.
110. Nozick, R. *Anarchy, State, and Utopia*; John Wiley & Sons: Hoboken, NJ, USA, 1974; ISBN 978-0465051007
111. Dorfman, R. A formula for the Gini coefficient. *Rev. Econ. Stat.* **1979**, *61*, 146–149. [CrossRef]
112. Wardrop, J.G. Road paper. some theoretical aspects of road traffic research. *Proc. Inst. Civ. Eng.* **1952**, *1*, 325–362. [CrossRef]
113. Varaiya, P. Max pressure control of a network of signalized intersections. *Transp. Res. Part C Emerg. Technol.* **2013**, *36*, 177–195. [CrossRef]
114. Baluja, S.; Covell, M.; Sukthankar, R. Traffic lights with auction-based controllers: Algorithms and real-world data. *arXiv* **2017**, arXiv:1702.01205. [CrossRef]
115. Lopez, P.A.; Behrisch, M.; Bieker-Walz, L.; Erdmann, J.; Flötteröd, Y.P.; Hilbrich, R.; Lücken, L.; Rummel, J.; Wagner, P.; Wießner, E. Microscopic Traffic Simulation using SUMO. In *Proceedings of the 21st IEEE International Conference on Intelligent Transportation Systems*; IEEE: Piscataway, NJ, USA, 2018. [CrossRef]
116. Arneson, R.J. Luck egalitarianism and prioritarianism. *Ethics* **2000**, *110*, 339–349. [CrossRef] [PubMed]
117. Riehl, K.; Kouvelas, A.; Makridis, M.A. Urban Priority Pass: Fair signalised intersection management accounting for passenger needs through prioritisation. *Transp. Res. Interdiscip. Perspect.* **2026**, *37*, 101988. [CrossRef]
118. Coulter, P.B. *Measuring Inequality: A Methodological Handbook;* Routledge: Abingdon, UK, 1989; ISBN 9780367162887.
119. Shannon, C.E. A mathematical theory of communication. *Bell Syst. Tech. J.* **1948**, *27*, 379–423. [CrossRef]
120. Lorenz, M.O. Methods of measuring the concentration of wealth. *Publ. Am. Stat. Assoc.* **1905**, *9*, 209–219. [CrossRef]
121. Theil, H. The Information Approach to Demand Analysis. *Econometrica* **1965**, *33*, 67–87. [CrossRef]
122. Palma, J.G. Homogeneous middles vs. heterogeneous tails, and the end of the 'inverted-U': It's all about the share of the rich. *Dev. Change* **2011**, *42*, 87–153. [CrossRef]

123. Atkinson, A.B. On the measurement of inequality. *J. Econ. Theory* **1970**, *2*, 244–263. [CrossRef]
124. Herfindahl, O.C. Concentration in the Steel Industry. Ph.D. Thesis, Columbia University, New York, NY, USA, 1950.
125. Hoover, E.M. The measurement of industrial localization. *Rev. Econ. Stat.* **1936**, *18*, 162–171. [CrossRef] [PubMed]