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16. Abstract

This research outlines three major challenges of incorporating Environmental Justice (EJ) into metropolitan transportation planning and proposes a new variation of the user equilibrium discrete network design problem (UE-DNDP) for achieving EJ amongst population groups.. Needed data is compared with what is currently available on spatial distribution of race and income, spatial distribution of trip ends, trip tables, network performance, and cost estimates of improvements. Several conflicting definitions of equity are offered, as well as applications for each within the context of EJ. The importance of choosing a correct unit of analysis is discussed, with particular emphasis on how the geographic unit of analysis is a poor proxy for the group unit – that is theoretically required as the analysis' purpose is to compare performance measures between groups.

Research into the UE-DNDP examines nine potential objective functions focused on maximizing equity of congestion and travel time. Assuming knowledge of the origin-destination travel matrices by population group, numerical analysis is conducted to assess the performance of each proposed formulation. The lower level UE problem is solved using the Frank-Wolfe method, and due to the hard combinatorial nature of EJ-UE-DNDP, a selectorecombinative genetic algorithm is implemented to efficiently search the solution space for feasible network improvement strategies. The results of numerical analysis suggest that both pareto-optimal and utility-based approaches can be successfully applied, and that the most effective formulations minimize the difference between the change in congestion or travel time across population groups due to the selected improvement projects.

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Incorporating Environmental Justice Measures into Equilibrium-based Transportation Network Design Models

by
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Research Report SWUTC/07/167265-1

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Disclaimer

ABSTRACT

This research outlines three major challenges of incorporating Environmental Justice (EJ) into metropolitan transportation planning and proposes a new variation of the user equilibrium discrete network design problem (UE-DNDP) for achieving EJ amongst population groups.. Needed data is compared with what is currently available on spatial distribution of race and income, spatial distribution of trip ends, trip tables, network performance, and cost estimates of improvements. Several conflicting definitions of equity are offered, as well as applications for each within the context of EJ. The importance of choosing a correct unit of analysis is discussed, with particular emphasis on how the geographic unit of analysis is a poor proxy for the group unit – that is theoretically required as the analysis' purpose is to compare performance measures between groups.

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EXECUTIVE SUMMARY

This research outlines three major challenges of incorporating Environmental Justice (EJ) into metropolitan transportation planning and proposes a new variation of the user equilibrium discrete network design problem for achieving EJ (EJ-UE-DNDP) amongst population groups.. Needed data is compared with what is currently available on spatial distribution of race and income, spatial distribution of trip ends, trip tables, network performance, and cost estimates of improvements. Several conflicting definitions of equity are offered, as well as applications for each within the context of EJ. The importance of choosing a correct unit of analysis is discussed, with particular emphasis on how the geographic unit of analysis is a poor proxy for the group unit – that is theoretically required as the analysis' purpose is to compare performance measures between groups.

Increased use of household travel survey data, activity-based models, and microsimulation may alleviate some of the data needs. Before starting an EJ analysis, an MPO must decide what type of equity it is trying to achieve and how it will treat the potentially different needs of its population groups. The choice between group and geographic unit must be made carefully as each has advantages and pitfalls. As transportation planners explore new types of projects and new sources of funding, equity analyses will become more complex. For example, it is becoming more common for metropolitan planning agencies to devote funding to land use improvements with the goal of reducing auto use or efficiently using the existing transportation network. The impact of land use improvements, such as transit-oriented development, on various sectors of the population has not yet been studied extensively. Equitable distribution of these projects across a region does not ensure equitable impacts as low-income populations may be "priced out" if gentrification occurs.

The increasing popularity of toll roads, managed lanes, and comprehensive development agreements with private developers pose new challenges for equity analyses. The distinction between public and private goods in transportation has always been blurry, as persons must purchase the appropriate equipment (i.e. auto, bicycle, shoes) to use most modes of travel. MPOs, with the assistance of the public and stakeholders, must make difficult decisions as to how to meet the transportation needs of their region without limiting access and benefits for specific groups.

Research into the EJ-UE-DNDP examines nine potential objective functions focused on maximizing equity of congestion and travel time. Assuming knowledge of the origin-destination travel matrices by population group, numerical analysis is conducted to assess the performance of each proposed formulation. The lower level UE problem is solved using the Frank-Wolfe method, and due to the hard combinatorial nature of EJ-UE-DNDP, a selectorecombinative genetic algorithm is successfully implemented to efficiently search the solution space for feasible network improvement strategies. The results of numerical analysis suggest that both pareto-optimal and utility-based approaches can be successfully applied, and that the most effective formulations minimize the difference between the change in congestion or travel time across population groups due to the selected improvement projects.

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CHAPTER ONE - INTRODUCTION

In the twelve years since Executive Order 12898, "Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations" (*1*), was issued, much progress has been made in formalizing Environmental Justice (EJ) analyses within transportation planning. However, as Metropolitan Planning Organizations (MPOs) produce long-range plans approximately every five years, formal EJ analyses of these plans are still in their infancy. To date, most of the research on EJ analyses in transportation planning has focused on specific analysis techniques (*2,3*), or the equity impacts of specific projects (*4-7*), modes (*8-10*), and funding structures (*11,12*). While such discussions are of obvious importance, this research focuses on three major challenges that have received limited attention in the context of long-range planning:

1) Collecting needed data,
2) Coming to a consensus as to how equity should be defined and applied in the context of EJ, and
3) Using an appropriate unit of analysis

After an analysis of the challenges facing the incorporation of EJ in transportation planning, the focus will be on presenting a new formulation for considering EJ criteria in the selection of network improvement projects, the Environmental Justice-User Equilibrium-Network Design Problem (EJ-UE-DNDP). Many questions remain as to how Environmental Justice (EJ) should be defined and what performance measures are appropriate to determine whether an adverse impact will occur (*2-4*). To address this debate, several objective functions are proposed that account for various interpretations of EJ.

To the authors' knowledge, this is the first research into considering EJ directly within the UE-DNDP. Part of the reason for this omission is that socio-economic details such as income and race that are used in the first three steps are lost in the final step, which relies solely on a matrix of zone-to-zone travel demands by mode. The volumes reported from route choice are in units of vehicles per hour, aggregated over all possible types of drivers. Therefore it is very difficult to make statements about the EJ impacts of transportation projects that are chosen based on volume or a volume to capacity ratio exceeding a specified threshold. Some planners may estimate EJ benefits and burdens based on the location of the roadway improvement, assuming that those who benefit most from a project live in its vicinity. This is typically done in a qualitative way (i.e. population X is receiving approximately the same number of improvements as population Y), and the purpose of this research is to quantify these impacts using network analysis. A network analysis approach is needed because placing improvements in a resident's zone is not always the most beneficial option for that individual. Rather, it is possible that this person would be better off if a bottleneck that he faces fifteen minutes into his morning commute was removed.

The foundation for the EJ-UE-DNDP, the UE-DNDP, has been treated numerous times in the literature. Steenbrink (*13*) and LeBlanc (*14*) implement branch and bound solution methods, where UE flows in the first paper are approximated by the easier to obtain system optimal flows. Poorzahedy and Turnquist (*15*) use a heuristic to approximate the UE-DNDP objective function as a single level UE function of flows and capacity. Gao et al. (*16*) use generalized Bender's decomposition to describe the relationship between flows and the addition of new links to the network in a finite number of iterations. Boyce and Janson (*17*) formulate three DNDPs with combined traffic assignment and trip distribution. Similar combined methods may be useful for future research into EJ-UE-DNDP as the EJ determination is strongly linked to land use and location choice. For a more thorough review of the UE-DNDP literature see Magnanti and Wong (*18*) or Gao et al. (*16*). The continuous version of this problem, UE-CNDP, has been researched more extensively in the literature than its discrete equivalent because its properties (continuity and differentiability) are amenable to a wider range of solution methods. CNDPs, however, will not be reviewed in this report as their solution methods are rarely applicable to DNDPs.

While EJ has not been considered previously within the NDP, other types of equity have received some attention. Meng and Yang (*19*) examine equity amongst travelers distinguished by origin-destination (OD) node pair in the UE-CNDP. A bi-criterion objective function is used to minimize total system cost and the maximum ratio of post-improvement travel cost to pre-improvement travel cost across all OD pairs. Connors et al. (*20*) use a probit stochastic UE model with elastic demand and user classes differentiated by value of travel time to set class-dependent tolls. The tolls are selected such that social welfare, defined as the sum of consumer surplus and operator benefit, is maximized while bounding the Theil equity measure from above. Szeto and Lo (*21*) use a UE-CNDP with elastic demand to examine social equity, defined as the per capita sum of discounted consumer surplus and discounted profit, and user equity, measured as discounted OD travel cost, across generations by modeling a long planning horizon with several design periods. Maruyama and Sumalee (*22*) compare pricing strategies using a trip chain-based equilibrium model according to a Marshallian rule of social welfare and the Gini coefficient. In all of these papers, the type of equity considered is not applicable to EJ analyses, which focus on equity amongst protected (i.e. minority or low-income) and unprotected population groups. For the remainder of the report, the terms EJ and equity will be used interchangeably.

This research presents a new method for using network analysis to select capacity improvement projects that best meet EJ criteria through the EJ-UE-DNDP model presented in the Chapter 3. As the exact definition of EJ may differ by agency, several relevant objective functions are tested. The bilevel problem posed is discontinuous due to the use of integer variables to represent capacity improvements, necessitating a heuristic solution method. Following the problem formulation, a genetic algorithm (GA) solution method is described, which is based on GA approaches that have proven successful in similar variations of the UE-DNDP. The solution method takes advantage of neighborhood effects and efficiently searches the non-convex solution space. Numerical analysis is conducted using a small network to gain insights into the EJ-UE-DNDP, with a particular focus on selecting an appropriate objective function. Finally, conclusions are presented along with recommendations for future research.

CHAPTER TWO – INCORPORATING EJ INTO METROPOLITAN TRANSPORTATION PLANNING

DATA NEEDS AND AVAILABILTY

Collecting the appropriate types of data in sufficient quantities for rigorous analysis is a challenge that pervades all of transportation planning. This section looks at five types of data that are needed for determining the Environmental Justice implications of a long-range plan, comparing what is available currently with what is ideally needed for both a base year and future years. The data types considered are the spatial distribution of race and income, spatial distribution of trip ends, trip tables, network performance, and cost estimates of improvements.

When obtaining any type of data, its accuracy should be questioned. Long-range plans or Metropolitan Transportation Plans (MTPs) forecast anywhere from twenty to fifty years into the future. Demographics forecasts are known to be subject to much uncertainty (*23*), and the finer the level of data required (i.e. locations of retail businesses instead of locations of total businesses) and the longer the amount of time between the base and forecast years, the more uncertainty there is. Hirschman (*24*) details the assumptions in projections of demographics by race and ethnicity, and Smith and Nogle (*25*) study projections of the Hispanic population and conclude that the errors tend to be larger for this group than for the total population.

Spatial Distribution of Race and Income

The Decennial Census provides information on the race of each person and the income level of each household at the block group level. For most MPOs, demographic forecasts output total residents and total employment by type in each zone or district, but do not forecast the spatial distribution of race or income. Without predictions of spatial distributions of race and income, future year distributions are typically assumed to be the same as in the base year. A comparison of 1990 and 2000 census data for many regions will show this assumption to be a poor one, but there are few alternatives. Purvis (*26*) describes the difficulty in obtaining predictions of race and income for EJ analyses, commenting that federal and state forecasts typically continue past trends.

Spatial Distribution of Trip Ends

In a growing region, keeping abreast of new developments (i.e. subdivisions and shopping centers) can be a full-time job, and predicting the location of development years into the future is near impossible. Despite data on existing development, trends, topography, and land use restrictions, the locations chosen by developers are not predictable with any degree of accuracy. The uncertainty about future development is important not only for determining future trip tables, but also for determining future accessibility to important locations. Several MPOs compare access to critical non-work locations such as schools and health care facilities across protected and unprotected classes. As residential and commercial developments sprawl, so do schools and hospitals. However, without more information, the locations of these facilities are assumed to remain unchanged in the future. Increased cooperating between transportation and land use planners and school and hospital administrators could reduce the level of surprise at new developments. Even current year data can be difficult to work with in some cases because not all health care facilities accept low-income people, not every job is suited for every person, and not all children can attend their neighborhood school.

Trip Tables

Accurate trip tables are important for the many EJ performance measures related to accessibility, comparing travel times to employment and other critical locations. (See reference *27* for a comprehensive overview of such measures). If trip tables were available by minority and income classes, much more could be done to measure accessibility. Segmented trip tables would allow select link analysis to determine how many people from each class will benefit from a particular roadway or transit project. Without this, accessibility measures must assume that the percentage of trips between each OD pair made by a specific class is equal to the percentage of residents at the origin that are a member of the class. This assumption is rather arbitrary and could be improved using information from household survey data.

A second issue with future year trip tables related to EJ is the potential to reinforce existing inequities. According to Deka (*28*), "if workers who live in predominantly low-income and minority areas have short commutes at present, computer models will predict a short commute for them in the future as well, regardless of their true commuting needs." This implies that network improvements may be based on the paths where people are currently traveling, not on the paths where they would like to travel. By making it easier for them to travel on their current path, you're helping them continue the status quo rather than helping them get where they would like to go. This is a much greater concern with gravity-based models, than with models employing destination choice.

Network Performance

Measures of network performance based on results from a travel model are mostly limited to expected volumes, delays, and travel times. As models are calibrated to expected conditions, the model results including EJ-related performance measures are approximates of the expected performance. Unfortunately this leaves out one important measure of performance – reliability. Performance measures capturing reliability of travel time would aid not only EJ analysis, but other transportation analyses as well. Resulting performance measures may be misleading if average measures are used, since two groups may have the same average time, but one group's access varies much more from day to day. Data collected from Intelligent Transportation Systems can aid in collecting the large amounts of data required for getting an accurate representation of current reliability. Future reliability may be more difficult to discern, but as research is conducted on trends leading to current levels of reliability, the ability to predict future levels of reliability will be improved.

Cost Estimates of Improvements

As will be discussed in the following section, EJ can be defined in terms of the impacts (i.e. travel time changes) on each population or in terms of the funding spent on improving conditions for each population. In order to estimate equity in funding, accurate cost estimates must be obtained for each improvement specified in the long-range plan. The difficulty with this is assuming inflation rates and costs of construction in future years. Also, the MTP may specify categories of spending instead of specific projects, making the benefit to each population group impossible to discern.

State-of-the-art travel models that rely on microsimulation to track activity patterns promise to alleviate some of these data issues. Household survey data could perhaps be used more extensively to synthesize trip tables and behavior specific to each population group. There is however the danger that such tools will improve precision of results without improving accuracy. The following section describes the various ways in which equity may be defined in the context of Environmental Justice.

EQUITY

This section reviews several definitions of equity presented in the literature, three main applications for equity in long-range planning, and multiple methods for approaching the time frame and scope of analysis. The purpose of this section is to stress that calculating performance measures is a futile effort unless it is certain what type of equity is achieved because after the calculations are complete there will be numbers without a sense of whether or not an injustice has occurred.

Defining Equity

Reaching an agreement as to which type of equity should be applied in an EJ analysis is not easy and all of the options should be weighed. More definitions of equity are found in the literature than can be concisely presented here. Four types of equity most applicable to transportation planning will be presented and they are referred to here as "Opportunity," "Equality," "Market-Based," and "Basic Needs." The Federal Highway Administration does not provide clear guidance on how to define equity, so the decision is left up to the MPOs.

Opportunity

Equity of opportunity is most often defined as each person or group having equal access to the planning process and having their opinions taken into account in an equal manner. The first step many MPOs take towards fulfilling the EJ requirements is outreach to the traditionally underserved populations. This can take several forms including hosting public meetings in protected areas at convenient times of day for working people and ensuring easy access by non-auto modes, and providing translators for persons who are not fluent in English.

Equality

Equality – what is typically thought of as a synonym of equity - entails making comparisons between performance measures, with the goal of equal benefits for each population. Within the context of equality, one can consider equal benefits in a future year or an equal change in benefits over time. As the needs and desires of people differ, equity in benefits may be achieved even if the actual benefits received by each group are different. Equality can also be considered in terms of allocation of funding.

Market

Market-based equity means "you get what you pay for." Several studies evaluate how well market-based equity is achieved in transportation financing (*11,12*), comparing how much a group pays in taxes and fees with the resources and benefits it receives. Taylor (*29*) also refers to this as market equity; Litman (*30*), Khisty (*31*), and Lee (*32*) refer to this as horizontal equity.

Basic Needs

Meeting basic needs is a compromise between the first two types of equity. First the basic needs of each person are met, and then any remaining resources and benefits are distributed according to market-equity. Khisty (*31*) describes it best as "bread for all, before butter for some."

Deciding which type of equity to strive for does not, by itself, make the selection of plans or projects amongst alternatives straightforward. If plan A offers each of two groups $10 in benefits, and plan B offers the first group $10 and the second group $15, should plan A be chosen on grounds of equity? Khisty (*31*) uses a small network to demonstrate how the optimal network improvements differ depending on the type of equity considered.

Guidance from FHWA as to distribution of funding and impacts is conflicting. A memorandum issued in January of 2000 (*33*) states that one of the three basic principles of EJ is to "assure low-income and minority groups receive proportionate share of benefits." However, the current FHWA policy as stated on its website (*34*) is that beyond the requirement to mitigate disparate impacts "there is no presumed distribution of resources to sustain compliance with the Environmental Justice provisions."

Applications of Equity

Equity determinations are three-fold, examining first the equity in public participation, then equity in funding, and lastly the equity in impacts. Since the focus of this research is on technical methods, this section will look primarily at equity in funding and equity in impacts. Giving each population group equal access to the planning process is extremely important; however, unlike funding and impacts, it is not easily measured by quantitative tools. First, it should be noted that equitable funding does not imply equitable impacts. For example, group A and group B could be allocated equal funds, but if A decides to use its funds to run a highway through the center of B's community, the resulting impacts will likely be inequitable.

Distribution of impacts and funding into the future is difficult to measure because metropolitan transportation plans (MTPs) cannot, due to their long time frame, specify projects in great detail. Much of the money allocated in MTPs goes towards programs that act as funding mechanisms for projects to be specified at a later date. Some entries in the MTP such as capacity improvements on a corridor may contain more detail than entries such as a program for funding intelligent transportation systems (ITS). Until projects are selected, there is no accurate way of evaluating the impact that will be felt by each population. Any calculation of program benefits that occurs before projects are selected will be a rough regional estimate, unsuited for group-level analysis. It is similarly difficult to determine years in advance the distribution of funding among population groups as it is not specified as such in the plan.

While future funding can be estimated, the exact amount of money available for a particular MTP is not known with certainty either. Revenue from fuel taxes depends on vehicle usage and efficiency, and political pressures exist to keep them from rising with inflation. Toll roads may bring in another source of revenue, albeit uncertain, as their popularity increases. Private investment in toll roads is an increasingly enticing option for regions in need of upfront money for new projects. Money available for transit depends not only on fares, but also the political climate and public sentiment. Despite all of the funding uncertainty however, if the planned funding is distributed equitably and the removed or additional funding is removed or added equitably, then the final funding distribution should be equitable.

Static vs. Changing Time Frame

Perhaps the most controversial aspect of impact evaluation is the time frame considered. Impacts can be assessed in the future year, or through the change in impacts from the base year to the future year. At the core of this debate is whether or not Environmental Justice should redress past injustices. For example, if the MTP improves travel times for groups A and B by ten minutes each, but A's base year travel time is 30 minutes longer than group B, is the MTP equitable? Most MPOs, by focusing on the change in measures during the planning period, would say yes, claiming that as long as their current and future actions impact each group proportionately, they are within the federal guidelines. While MPOs may be within their legal limits to evaluate impacts in this way, as long as disparities exist in transportation benefits and costs, sectors of the population will continue to feel that the system is not just. Equating future year performance measures, however, has its problems too. One issue with using future year travel times as a performance measure is that some populations, particularly those with higher incomes, may choose a longer commute in return for other benefits such as a larger house or better schools. It is obviously unreasonable to try to equate such a population's long commute time with the commute time of a lower-income population that lives in close proximity to its destinations.

Scope of Analysis

As stated previously, the purpose of considering EJ in the MTP is to ensure that no group is disproportionately adversely affected. Before an MPO can determine whether or not the plan is equitable, a decision must be made as to whether each performance measure is going to be looked at individually, or a holistic view will be taken in the analysis. Most practitioners and researchers would argue that the point of analyzing EJ in the MTP is so that the system can be evaluated as a whole; total benefits, costs, and funding should be compared across groups. Despite this apparent consensus, it is not uncommon for an EJ analysis to present many types of performance measures, without concluding whether or not a group is disproportionately adversely affected. This is more of an issue for impact equity than funding equity, since combining monetary units is simpler and requires fewer value judgments than combining various impact measures.

The difficulty in creating a system-level EJ determination is in how to combine the individual performance measure results. A survey of the population could tell the analyst which performance measures are most important, allowing the creation of a generalized utility term. One could make the problem even more difficult by allowing each sector of the population to have a different set of preferences. If each group is assumed to have the same transportation needs, then evaluating disparate impacts within programs or single performance measures is appropriate. If the needs of each group are different, however, a system-level analysis is the only way to determine EJ results. To find out the needs of the EJ populations, some MPOs have formed task forces composed of representatives from each group. Other MPOs, fearing an EJ task force will slow the planning process without being truly representative of the traditionally underserved groups, have increased public outreach efforts.

Once the needs of each group are defined, the trick is to evaluate equity in terms of how well each group's needs are met. If group A is primarily concerned with pedestrian access to destinations and group B cares about auto commute times, an equity analysis would measure how well A's need for better sidewalk connectivity is being met compared to the fulfillment of B's desire for increased freeway capacity. This example also illustrates a case where impact equity will lead to funding inequity, since sidewalk connectivity is cheaper to provide than roadway capacity. While a system level equity analysis requires more thought and public input than evaluating program level or performance measure disparities, it is much more intuitive and has the added benefit of ensuring that the transportation services provided are actually meeting the needs of the public.

Funding Equity at the Federal and State Levels

This research focuses on equity related to EJ in long-range planning; however, the topic of equity brings much debate in other areas of transportation. Most notable is the discussion of equity in the distribution of federal funds to states. When states argue that they are not getting their fair share of funds, they are usually implying that they are the subjects of market inequity. Currently, allocation of federal funds from the Highway Trust Fund ensures a pseudo-market equity in which each state receives at least a 90.5 percent rate of return based on its tax receipt contribution (*11*).

Funding distribution within states has also caused controversy. Denver Regional Council of Governments has worked with the state of Colorado in recent years to remedy a market inequity where the Denver metropolitan area was receiving fifty-four cents in funding for every one dollar it contributed (*35*). Washington created a statewide Transportation Improvement Account to funnel gas tax revenue to urban areas after it was discovered that Seattle raised fifty-one percent of the state's revenues and received only thirty-nine percent in return (*11*). Tennessee, Arkansas, Ohio, and Alabama distribute portions of transportation funds evenly among each county regardless of population and need (*11*). This type of geographical equity is argued to facilitate sprawl by spending proportionally more money in rural areas.

UNIT OF ANALYSIS

Environmental Justice compliance determinations can be made using one of the following units of analysis: individual, group, or geographic. The unit of analysis is the basis for comparison of performance measures. Most equity analyses for applications other than Environmental Justice use the individual unit of analysis. For example, Levinson *(36*) uses the Gini coefficient to measure the equity of ramp metering, and Connors et al. (*37*) seek toll rates that maximize the Theil entropy index used to measure social welfare. In theory, Environmental Justice uses the group unit of analysis, comparing impacts across groups defined by race, ethnicity, and income. Since adequate data is rarely available at the group level (i.e. trip tables disaggregated by group), most EJ analyses are done using geographic units. There are, however, several problems with this.

Traffic survey zone are defined as "protected" or "unprotected" based on its percentage of minority or low-income residents. Doing this accounts for neither the number of residents in a zone or its size. This means that zone A is protected if it has only one resident and this person's income is below the poverty line, but an adjacent zone B with ten low-income residents and ninety high-income residents will be unprotected if the threshold for classifying a zone as "low-income protected" is greater than ten-percent. This arbitrary distinction could be interpreted to mean that the one person in zone A is somehow valued more than the ten low-income residents of zone B. If the zonal boundaries change, perhaps neither zone would be protected. Also, the classification of a zone as protected or unprotected may change depending on how the groups are defined. For example, a racially and ethnically diverse zone may be "protected" under a "minority" designation, but "unprotected" if separate designations are used for each racial and ethnic class.

Using the geographic unit as a proxy for the group unit does not work well for groups that do not congregate spatially. While members of some minority groups may tend to reside in geographic proximity to one another, members of other minority groups may be more dispersed. This problem is especially evident when groups such as the disabled and the elderly are considered. Each zone may have an approximately equal percentage of members of a spatially distributed group, making determination of protected and unprotected zones arbitrary.

CHAPTER THREE – INCORPORATING EJ INTO EQUILIBRIUM-BASED NETWORK DESIGN

THE MODEL

The EJ-UE-DNDP presented in this research (Equations 1-8) is a mixed-integer bilevel problem where the lower level (Equations 3-8) solves for UE as originally formulated by Beckmann et al. (*38*). UE behavior is famously described in Wardrop's (*39*) first principle as *the journey times in all routes actually used are equal and less than those which would be experienced by a single vehicle on any unused route.* Constraints 3-5 ensure that vehicle flows are balanced at each node, all travel demand is satisfied, and all flows are non-negative, respectively. The upper level problem (Equations 1 and 2) has the goal of selecting network improvements such that EJ is achieved. As discussed in the introduction, a precise definition of EJ is lacking so the objective function is tentatively left in general form. Equation 2 restricts the number of links selected to a constant value θ. The upper level EJ-UE-DNDP was formulated in this manner because this research was initially motivated by the practical problem of selecting intersection improvements that satisfy EJ requirements. Intersection improvements often have similar costs and, when selected for an entire region, a macroscopic traffic assignment model is typically used to evaluate the transportation system impacts by treating the improvements as capacity additions. This equation can be easily converted to a budget constraint; however, it should be noted that changing the constraint will alter the discussion of complexity later in this section. A DNDP approach was selected over a CNDP approach to this problem for similar reasons.

$$\min_{g\in\{0,1\}} Z(v^*(g), g) \quad (1)$$

$$s.t. \sum_{l\in L\setminus I} g_l = \theta \quad (2)$$

$$v^*(g) = \arg\min_{v} \sum_{l\in L} \int_{x=0}^{v_l} t_l(x)dx \quad (3)$$

$$s.t.\ v = Ah \quad (4)$$

$$d = Bh \quad (5)$$

$$v \geq 0 \quad (6)$$

$$t_l(v_l, g_l) = t_l(0)\times\left(1+\alpha\left(\frac{v_l}{u_l + g_l\gamma}\right)^{\beta}\right), \quad \forall l \in I \quad (7)$$

$$t_l(v_l) = t_l(0)\times\left(1+\alpha\left(\frac{v_l}{u_l}\right)^{\beta}\right), \quad \forall l \in L\setminus I \quad (8)$$

Here, l is the link index, L is the set of all links in the network, and I is the subset of L containing only the links under consideration for improvement. The travel time function for link l, $t_l(.)$, is a function of the vector of link flows, v. For $l \in I$, $t_l(.)$ is also a function of selected capacity improvements, g. The link-path incidence matrix, A, creates a one-to-one correspondence between h, the vector of path flows, and v. The OD-path incidence matrix, B, creates a one-to-one correspondence between, d, the matrix of demands between each OD pair and h. Finally, α and β are parameters of the link cost function, and γ is the amount of capacity that will be added if a link is selected for improvement.

Unlike most other DNDP formulations the number of links selected for improvement is known a priori. This changes the computational complexity of the problem from exponential ($O(2^I)$) to pseudo-polynomial. It can be shown using Stirling's Approximation $\left(n! \approx \sqrt{2\pi n}\frac{n^n}{e^n}\right)$ that $\lim_{g\to\infty} E[N] = O(g^\theta)$, where N is the number of samples required before finding the optimal solution. A random search could be used to solve small versions of this problem. If samples are taken without replacement, $E[N] = \frac{\sum_{n=1}^{C_\theta^g} n}{C_\theta^g} = \frac{1}{2}\left(C_\theta^g + 1\right)$, where C is the combination operator $C_\theta^g = \frac{g!}{(g-\theta)!\theta!}$. If samples are taken with replacement, then $E[N] = \sum_{n=1}^{\infty}\left(\frac{n}{C_\theta^g}\right)\left(\frac{C_\theta^g - 1}{C_\theta^g}\right)^{n-1} = C_\theta^g$. For problems with a larger number of improvement projects being considered, a heuristic approach is clearly needed as g^θ quickly becomes too large to solve by enumeration, and the overall EJ-UE-DNDP is non-convex meaning local search techniques are unlikely to yield a global optimal solution. The complexity of the problem also depends on the choice of the upper level objective function $Z\left(v^*(g), g\right)$. Nine candidates for $Z\left(v^*(g), g\right)$, which has until now been treated generally, are discussed in the next section.

Objective Functions

As discussed in the introduction, a precise definition of EJ is not available. In choosing objective functions for the upper level of EJ-UE-DNDP, two considerations must be made: the selection of appropriate performance measures (PM) (i.e. benefits caused by the network improvements that should be maximized), and the choice of a time frame for evaluation (*2*). The nine objective functions evaluated in this research are shown in Figure 1 and are discussed in the following paragraphs.

$$Z_1 = \frac{\sum_{ij} s_{ij}^f d_{ij} p_{ij} / e_{ij}^f}{\sum_{ij} d_{ij} p_{ij}}; \qquad Z_2 = \frac{\sum_{ij} s_{ij}^f d_{ij} / e_{ij}^f}{\sum_{ij} d_{ij}};$$

$$Z_3 = \left(\frac{\sum_{ij} s_{ij}^f d_{ij} p_{ij} / e_{ij}^f}{\sum_{ij} d_{ij} p_{ij}} - \frac{\sum_{ij} s_{ij}^f d_{ij} (1 - p_{ij}) / e_{ij}^f}{\sum_{ij} d_{ij} (1 - p_{ij})} \right)^2;$$

$$Z_4 = \left(\frac{\sum_{ij} \left(s_{ij}^f d_{ij} p_{ij} / e_{ij}^f - s_{ij}^0 d_{ij} p_{ij} / e_{ij}^0 \right)^2}{\sum_{ij} d_{ij} p_{ij}} - \frac{\sum_{ij} \left(s_{ij}^f d_{ij} (1 - p_{ij}) / e_{ij}^f - s_{ij}^0 d_{ij} (1 - p_{ij}) / e_{ij}^0 \right)^2}{\sum_{ij} d_{ij} (1 - p_{ij})} \right)^2;$$

$$Z_5 = \frac{\sum_{ij} s_{ij}^f d_{ij} p_{ij}}{\sum_{ij} d_{ij} p_{ij}}; \qquad Z_6 = \frac{\sum_{ij} s_{ij}^f d_{ij}}{\sum_{ij} d_{ij}};$$

$$Z_7 = \left(\frac{\sum_{ij} s_{ij}^f d_{ij} p_{ij}}{\sum_{ij} d_{ij} p_{ij}} - \frac{\sum_{ij} s_{ij}^f d_{ij} (1 - p_{ij})}{\sum_{ij} d_{ij} (1 - p_{ij})} \right)^2;$$

$$Z_8 = \left(\frac{\sum_{ij} \left(s_{ij}^f d_{ij} p_{ij} - s_{ij}^0 d_{ij} p_{ij} \right)^2}{\sum_{ij} d_{ij} p_{ij}} - \frac{\sum_{ij} \left(s_{ij}^f d_{ij} (1 - p_{ij}) - s_{ij}^0 d_{ij} (1 - p_{ij}) \right)^2}{\sum_{ij} d_{ij} (1 - p_{ij})} \right)^2;$$

$$Z_9 = \sum_{k=1}^{8} \lambda_k (Z_k)^{\omega_k}$$

FIGURE 1 Objective Functions

The following notation is used in describing the nine objective functions in Figure 1: s_{ij}^0 and s_{ij}^f are the shortest path travel time from origin *i* to destination *j* before and after the improvements are made, e_{ij}^0 and e_{ij}^f are the shortest path distances from *i* to *j* before and after the improvements are made, d_{ij} is the total travel demand from *i* to *j*, and p_{ij} is the proportion of trips from *i* to *j* made by persons in the protected population. In Z_9, λ_k and ω_k are used to weight each of the previous eight objective function values. For simplicity, only two population groups are considered in this research, one protected and one unprotected. However, the transition to considering three or more population groups would be trivial. The remainder of this section is an explanation of the characteristics of Z_1 through Z_9.

Minimize Congestion or Travel Time

Congestion and travel time are the two performance measures evaluated in this research as they are primary concerns of all travelers and are also natural outputs of the traffic assignment problem. Congestion is defined in objective functions Z_1, Z_2, Z_3, and Z_4 as travel time per unit length or s_{ij}/e_{ij} . Reducing congestion is often the primary motivation behind network improvement projects and Z_3 and Z_4 seek to ensure that this is done equitably. Z_1 and Z_2 do not specifically target equity, but are nonetheless useful as an index for performance if the focus is on protected populations or the entire population. As discussed in the introduction, the distribution of travel times across population groups is a commonly used measure in EJ analyses. Objective functions Z_5, Z_6, Z_7, and Z_8 seek to minimize travel time, with Z_7 and Z_8 seeking equity in travel time and Z_5 and Z_6 minimizing travel time for the protected population and total population, respectively.

It should be noted that the choice of using congestion or travel time as a PM must be done with care. Since the EJ-UE-DNDP does not currently take into account factors related to the selection of origins and destinations, unintended consequences may occur. For example, if Z_7 is used then the optimal network improvements may be directed at improving conditions for a wealthy population group whose members chose residences far from their workplaces in order to enjoy non-travel time benefits such as a larger house or a better school district. However, the opposite situation could also occur where a population group is priced out of living close to its primary destinations.

Compare Post-Improvement Equity or the Change in Equity due to Network Improvement
The choice of a time frame for evaluation addresses the debate over whether the purpose of EJ is to redress past injustices by comparing the post-improvement PMs across population groups, or only to ensure that the current plan is equitable by comparing the change in PMs from pre- to post-improvement across groups. Striving to achieve equity amongst population groups after project implementation is aligned with the philosophy of using the network projects as a means to redress past injustices to disadvantaged groups. Objective functions Z_3 and Z_7 seek this type of static equity by minimizing the difference in post-improvement congestion and travel time, respectively, across population groups. Comparing the change in equity due to the selected network improvement strategy allows the modeler to evaluate the direct EJ impact of the transportation plan. Objective functions Z_4 and Z_8 seek this type of equity by minimizing the difference in congestion and travel time, respectively, caused by the improvement strategy across population groups.

Utility Function Approach
Objective function Z_9 is a general utility function, allowing for weights and exponents on each of the previous eight objective functions in order to properly scale each according to the units and user preference. It is unlikely that Z_9 will be used with all weights taking positive values, but several forms of the function where the weights on conflicting variables (i.e. Z_3 and Z_4) are non-zero could provide a very useful approach to this problem.

SOLUTION METHOD

Although the lower level problem of EJ-UE-DNDP is continuously differentiable, a heuristic solution method is required due to the discontinuity in the upper level problem stemming from the use of integer variables. A GA approach is adopted because its intrinsic parallelism provides an efficient search of the global solution space and similar approaches have proven successful in other applications of the UE-DNDP (*40-42*). Unlike random search heuristics, GA also takes advantage of any existing neighborhood effects, which in this research means considering network improvement strategies that are similar to a strategy that has been shown to perform well. The complexity of the upper level objective does not significantly increase the problem difficulty as its fitness is evaluated through a simple functional evaluation.

The notation used to describe a GA as applied to EJ-UE-DNDP is as follows: *chromosome* refers to a vector with length |I|, *gene* refers to the representation of an improvement project within the chromosome $g_l, \forall l \in I$, a *population* is a set of *c* chromosomes in the same *generation*, and *fitness* is an equivalent term for objective function value. For example, | 0 | 0 | 0 | 0 | 0 | represents a chromosome with all genes turned off (no improvement projects selected), and | 0 | 1 | 0 | 0 | 1 | represents a chromosome with two genes turned on (2nd and 5th projects are selected for improvement). Each generation a new population is evaluated and operated on to find the population of the next generation. Define the set $G = \left\{ g = (g_1, g_2, ..., g_I) \mid g_l \in \{0,1\}, \sum_{l \in I} g_l = \theta \right\}$ where the number of elements in the set G is C_θ^g. An outline of the GA algorithm as applied to EJ-UE-NDP is shown below. For a thorough discussion of GA approaches, see Holland (*43*) or Goldberg (*44*).

Step 0: Initialize Lower Level Solution

If objective functions Z_4 or Z_8 is used, solve UE with upper level variables $g_l = 0, \forall l \in I$ to find variables S^0 and e^0. If objective functions Z_1-Z_3 or Z_5-Z_7 are used, this step can be skipped.

Step 1: Initialize Population

Set the index for the current generation, n =1. Randomly select *c* chromosomes from the set *G* for the initial population, pop_n, subject to the upper level constraint 2.

Step 2: Solve Lower Level Problem

Solve UE using the Frank-Wolfe algorithm (*44*) for each chromosome in pop_n. Check for convergence (i.e. if $n = n_{max}$). If convergence is not yet reached, go to Step 3.

Step 3: s-Tournament Selection

For each group or "tournament" of *s* chromosomes, keep the best chromosome as a parent for generation n+1.

Step 4: Crossover

Let n=n+1. Create pop_n by performing pairwise uniform crossover operations on the parents with probability *Pc*.

Step 5: Mutation

Mutate each gene of each chromosome in pop_n with probability Pm. If a constraint is violated, randomly mutate a gene in the offending chromosome until the constraint is once again enforced. Go to Step 2.

CHAPTER FOUR – EXPERIMENTAL ANALYSIS AND RESULTS

NUMERICAL ANALYSIS

The formulation and solution method presented in the previous sections are implemented here on a small network to gain insights into the EJ-UE-DNDP problem, especially with regard to the selection of an appropriate objective function. This section describes the parameters employed in the utility-based objective function (Z_9), the transportation network used as a test-bed, and the chosen GA-parameters. Following these initial considerations is a presentation and discussion of the experimental results.

Objective Functions

Each of the nine objective functions depicted in Figure 1 are analyzed in this section. Objective functions Z_1-Z_8 are tested as described previously. For Z_9, the following parameters were used: $\lambda_1 = \lambda_2 = ... = \lambda_8$, $\omega_1 = \omega_2 = \omega_3 = \omega_5 = \omega_6 = \omega_7 = 1$, $\omega_4 = 0.5$, and $\omega_8 = 0.25$. The exponential coefficients ω_4 and ω_8 were chosen to achieve an approximate consistency in the scale of units. This is by no means an optimal or even necessarily intuitive parameter set for Z_9. The purpose of including Z_9 in this research is to evaluate whether utility-based objective functions have potential to present reasonable network improvement solutions. Further research is needed into the decision theory behind selecting the most effective parameters λ and ω.

Network Data

The EJ-UE-DNDP was solved on the 24-node and 76-link Sioux Falls, South Dakota network (Figure 2), identical to the one used in Meng and Yang (*19*). Twelve origin-destination pairs were considered, and the demand by population group is shown in Table 1.

TABLE 1 Origin-Destination Travel Demand with Proportion of Protected Persons in Parentheses

		Destination Node			
		6	7	18	20
Origin Node	1	600 (0.10)	900 (0.10)	800 (0.40)	0 (0.00)
	2	500 (0.25)	1200 (0.20)	0 (0.00)	900 (0.10)
	3	1860 (0.10)	0 (0.00)	500 (0.10)	1230 (0.30)
	13	0 (0.00)	400 (0.10)	600 (0.30)	1540 (0.30)

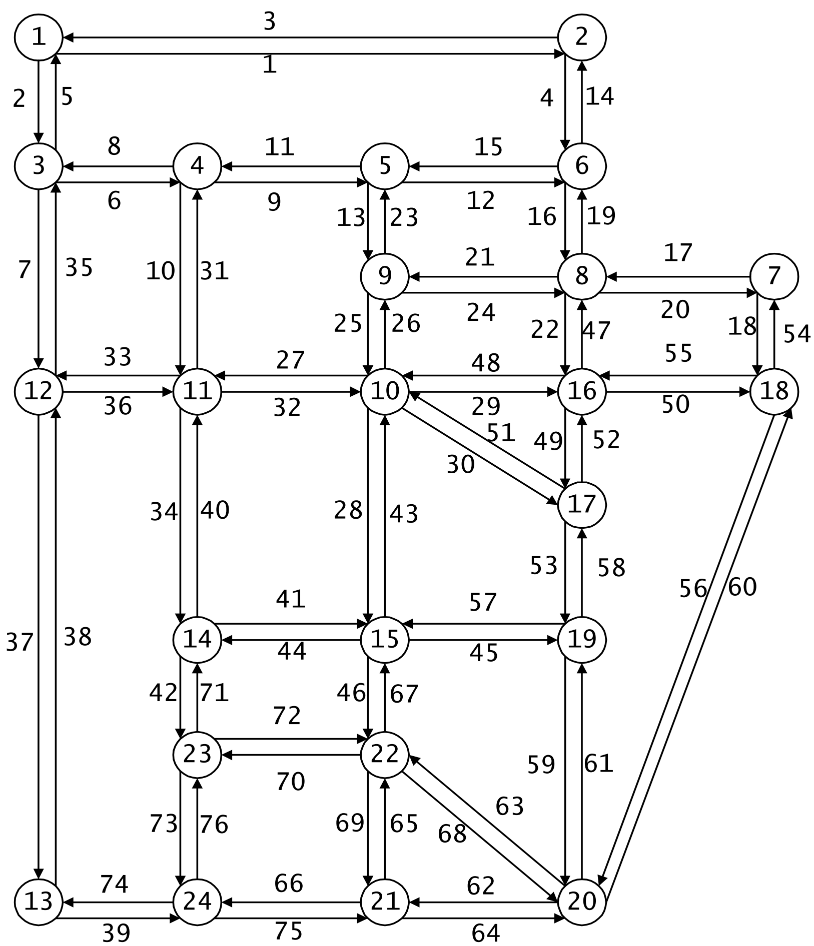

FIGURE 2 Sioux Falls Network (*11*)

GA Parameters

The structure of the GA used in this analysis was informed by previous research by Jeon et al. (*41*) into the optimal GA parameters for UE-DNDP, which suggested a selectorecombinative approach ($Pm = 0$) with Pc=0.85 and a tournament size s=10. All links are considered to be candidates for improvement ($I = L$) therefore the length of each chromosome is 76. The population size, c, was set by following guidelines provided by Goldberg (*44*), suggesting a value of approximately ten times the chromosome length (c = 760). Numerical testing using Z_1 was conducted to determine the number of generations required for convergence, $n_{converge}$ (see Figure 3). At n=15, Z_1 is within 0.001 of optimal, so n_{max} = 15 for all numerical tests.

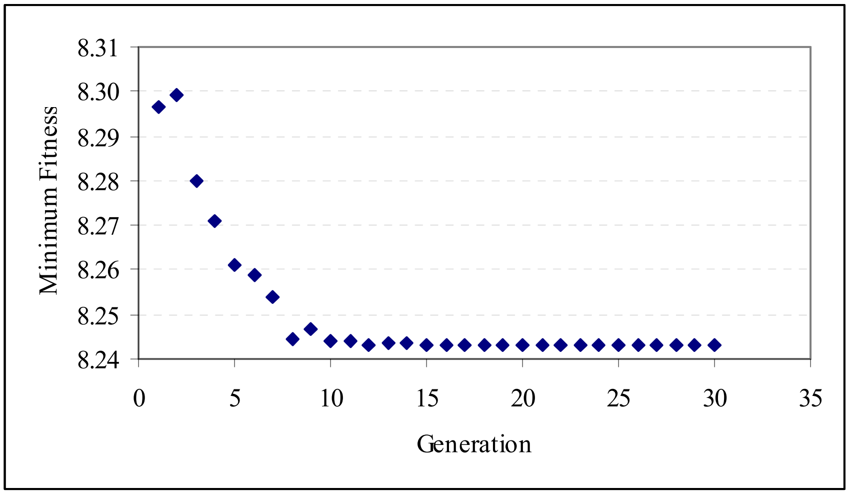

FIGURE 3 Convergence of Z_1

Results

Table 2 shows the minimum and maximum objective function values found after 15 generations. The last row, labeled $n_{converge}$, lists the number of generations required to converge the minimum value to within 0.001. The results suggest that the objective function values that measure the difference in travel time from pre- to post-improvement (Z_4, Z_8, and Z_9) vary substantially depending on the network design decision, even considering the scale of their units. The objective function values that use only the variable for post-improvement travel time do not vary in any way that would be noticeable to a traveler. This suggests that for this instance of the problem, Z_4, Z_8, or Z_9would be the appropriate choice of objective function. For Z_9, the coefficients should be altered such that $\lambda_k = 0, \forall k = 1..8 \;\; s.t. \left(Z_k^{\max} - Z_k^{\min}\right) < \varepsilon$, where ε is small enough that a traveler could not detect the difference in system performance.

TABLE 2 Range of Fitness and Number of Generations to Convergence

	Objective Function								
	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9
$\mathbf{Z^{min}}$	8.24	8.59	0.11	0	7.26	6.20	1.70	0	33.58
$\mathbf{Z^{max}}$	8.55	8.93	0.33	84909	7.44	6.35	1.91	189.17	84952.4
$\mathbf{n_{converge}}$	15	15	7	1	15	13	5	1	2

Table 3 shows the results of evaluating each objective function using the nine network improvement strategies that led to Z^{min} (see Table 2). The objective function used for minimization is designated by the row index and the objective function used for evaluation is designated by the column index. The italicized diagonal entries correspond to the Z^{min} row in the previous table. The results suggest that minimizing for Z_1, Z_2, Z_3, Z_5, Z_6, or Z_7 can have disastrous effects on the performance on Z_4, Z_8, and Z_9. A multi-objective utility-based approach such as Z_9 or pareto-optimality is clearly needed to balance the trade-offs between post-improvement equity and change in equity due to improvements.

TABLE 3 Fitness Tradeoffs

		Evaluate Objective								
		Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_4	Z_8	Z_9
Minimize Objective	Z_1	*8.24*	8.59	0.19	88637.9	7.26	6.20	1.78	206.75	88674.2
	Z_2	8.24	*8.59*	0.19	88626.8	7.27	6.20	1.78	204.99	88663.1
	Z_3	8.41	8.68	*0.11*	103525	7.35	6.25	1.91	312.39	103562
	Z_4	8.55	8.93	0.23	*0*	7.44	6.35	1.83	0	33.58
	Z_5	8.24	8.59	0.19	88546.8	*7.26*	6.20	1.78	206.32	88583.2
	Z_6	8.24	8.59	0.19	88372.6	7.26	*6.20*	1.78	204.61	88408.9
	Z_7	8.38	8.85	0.34	574.15	7.35	6.31	*1.70*	11.48	609.16
	Z_8	8.55	8.93	0.23	0	7.44	6.35	1.83	*0*	33.58
	Z_9	8.55	8.93	0.23	0	7.44	6.35	1.83	0	*33.58*

CHAPTER FIVE - CONCLUSIONS

Three challenges faced by Environmental Justice analyses in transportation planning were discussed in this research and a bilevel Environmental Justice-User Equilibrium-Discrete Network Design Problem (EJ-UE-NDP) was formulated. Data needs were identified, definitions and applications of equity were offered, and technical issues associated with the unit of analysis were presented. Increased use of household travel survey data, activity-based models, and microsimulation may alleviate some of the data needs. Before starting an EJ analysis, an MPO must decide what type of equity it is trying to achieve and how it will treat the potentially different needs of its population groups. The choice between group and geographic unit must be made carefully as each has advantages and pitfalls.

As transportation planners explore new types of projects and new sources of funding, equity analyses will become more complex. For example, it is becoming more common for metropolitan planning agencies to devote funding to land use improvements with the goal of reducing auto use or efficiently using the existing transportation network. The impact of land use improvements, such as transit-oriented development, on various sectors of the population has not yet been studied extensively. Equitable distribution of these projects across a region does not ensure equitable impacts as low-income populations may be “priced out” if gentrification occurs.

The increasing popularity of toll roads, managed lanes, and comprehensive development agreements with private developers pose new challenges for equity analyses. The distinction between public and private goods in transportation has always been blurry, as persons must purchase the appropriate equipment (i.e. auto, bicycle, shoes) to use most modes of travel. MPOs, with the assistance of the public and stakeholders, must make difficult decisions as to how to meet the transportation needs of their region without limiting access and benefits for specific groups.

A bilevel Environmental Justice-User Equilibrium-Discrete Network Design Problem (EJ-UE-NDP) was formulated in this research to solve the problem of achieving Environmental Justice (EJ) through a selection of network improvement strategies where EJ is defined to mean that no protected population is disproportionately adversely impacted. Several objective functions were proposed to meet the needs of the various interpretations of EJ encountered in practice. This research offers a significant contribution to the debate over whether the purpose of EJ is to redress past injustices or to ensure that only the current plan is equitable. A selectorecombinative genetic algorithm (GA)-based procedure was proposed to solve the EJ-UE-NDP based on its ability to model neighborhood effects, its intrinsically parallel search of the solution space, and its success on other variations of UE-DNDP. The GA method was successfully implemented on a small network, converging for each objective function after testing $O(10^4)$ network improvement strategies, whereas the expected number of strategies needed to find the global optimal in a random search strategy is $O(10^{17})$. The numerical analysis results suggest the following two objectives are conflicting: 1) minimizing the difference in post-improvement performance across populations and 2) minimizing the difference across populations in the change in performance due to improvements. This discovery makes multi-objective decision theory an attractive avenue for future research on this problem. An example weighted-average objective function was tested to show that utility-based multi-objective approaches are applicable.

Another interesting avenue for research on this topic is the development of a method for choosing candidate links. For typical applications of UE-DNDP, link-based ratios of volume to capacity can be used to not only create the list of candidates for improvement, but they can also be used for aiding the GA in searching the solution space more intelligently. A similar method could be developed for EJ-UE-DNDP, possibly based on measures describing the congested links heavily used by protected persons. Also, combining the EJ-UE-DNDP with a location choice model may alleviate some of the difficulties related to determining if a longer travel time is due to a disadvantage or if it is by choice. Expanding numerical analysis to more networks and instances of travel demand by population group is needed to generalize the conclusions of this research. Finally, for the model developed in this research to be transferable to practice, better data is needed on the variation in travel demand amongst population groups.

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