EQUITY CONSIDERATIONS IN TRANSPORTATION DECISION MAKING

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Equity and Transit System Performance Measurement
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Every transportation project has “winners” and “losers”...

...but some populations always seem to be on the losing side.
Many public transportation riders belong to politically vulnerable populations.

What does equity mean in the context of transit specifically, and what can be done to achieve it?
What to make of official guidance?

“In making determinations regarding disproportionately high and adverse effects on minority and low-income populations, mitigation and enhancements measures that will be taken and all offsetting benefits to the affected minority and low-income populations may be taken into account, as well as the design, comparative impacts, and the relevant number of similar existing system elements in non-minority and non low-income areas.”

--USDOT Order on Environmental Justice

What does “disproportionately high and adverse” mean?
Which of these situations is preferable?

**Scenario 1**

- Group A
- Group B

**Scenario 2**

- Group A
- Group B
Which of these situations is preferable?

**Scenario 1**

- Group A
- Group B

**Scenario 2**

- Group A
- Group B
There is also a distinction between **equality of inputs** and **equality of outcomes**.
So, what to make of equity in transportation planning?
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“I shall not today attempt further to define the kinds of material I understand to be embraced within that shorthand distinction, and perhaps I could never succeed in intelligibly doing so. But I know it when I see it...”

--Potter Stewart, Supreme Court Justice
However, today more and more **quantitative measures of effectiveness** are being demanded.

This talk discusses some ways of quantitatively measuring equity or inequity, and their amenability to the planning process.
A brief outline:

1. The resource allocation problem and transportation
2. Equity in the resource allocation problem
3. What works well in planning?
4. What to do about equity?

More generally, what is the proper role of mathematical modeling when dealing with “intangible” ethical considerations like equity?
RESOURCE ALLOCATION PROBLEMS AND TRANSPORTATION
In operations research, the resource allocation problem describes the following situation:

A decision maker is given a resource which can be distributed among alternatives. Each alternative results in a certain cost when given a certain level of resources. How should resources be divided to minimize the total cost?

In transportation, the “costs” are often disbenefits like congestion or unreliability.
How should frequencies be set on transit lines to minimize total user delay?

**Resources:** Vehicles in fleet

**Alternatives:** Transit lines

**Costs:** User delay on each line

(Ferguson et al., 2012)
Where should network improvements be made to improve reliability?

Resources: Available funding

Alternatives: Potential improvement projects

Costs: Travel time standard deviation

(Duthie et al., 2007)
How often should pavement be resurfaced?

Resources: Frequency of maintenance
Alternatives: Facilities in a system
Costs: User cost from driving on rough pavement

(Sathaye & Madant, 2011; Boyles, 2014)
Mathematically, the costs for each alternative can be plotted as a function of the resource allocated.

![Graph showing the cost of two alternatives relative to resources invested.]
Mathematically, the costs for each alternative can be plotted as a function of the resource allocated.

Total cost is minimized when the slopes of these functions are equal.
The resource allocation problem can then be stated as

\[
\min \sum_{i} f_i(x_i)
\]

subject to

\[
\sum_{i} x_i \leq B \quad x_i \geq 0
\]

where \(B\) is the resource budget, \(x_i\) is the amount allocated to alternative \(i\), and \(f_i(x_i)\) is the cost when alternative \(i\) gets \(x_i\) resources.
So far, there is no concept of equity (or even users).

Every alternative counts equally; but not all alternatives are equally used.
However, we can introduce different types of users and associate them with alternatives.

Now it is meaningful to talk about the costs associated with each user type.
If there are $N_j$ users of type $j$, then the average cost to these users are

$$C_j = \frac{\sum_i n_{ij} f_i}{N_j}$$

So for any possible resource allocation we can see what the average cost to each user type is, not just the “total” cost.
Can we come up with some metric for inequity then?

$$\min \sum_i f_i(x_i) + I$$

subject to

$$\sum_i x_i \leq B \quad x_i \geq 0$$

What should $I$ be?
HOW TO QUANTIFY INEQUITY?
To simplify things and give concrete examples, let’s assume (1) there are only two alternatives; (2) the goal is only to minimize inequity (not total cost).

$$\min I$$

subject to

$$x_1 + x_2 \leq B \quad x_1, x_2 \geq 0$$

What should $I$ be?
10 buses must be assigned to these two lines (at least one per line). How to do so while maximizing equity between groups 1 and 2? Currently, 5 buses serve each line.

Group 1

Group 2

Line A

High-crime neighborhood

CBD

Line B

(“line to nowhere”)
As a first attempt, what if we make $I$ the standard deviation of $C_1$ and $C_2$?
As a first attempt, what if we make $I$ the standard deviation of $C_1$ and $C_2$?

\[
I = (C_1 - \bar{C})^2 + (C_2 - \bar{C})^2
\]

Standard deviation is minimized if the difference between $C_1$ and $C_2$ is as small as possible.
Therefore, to minimize inequity, put 1 bus on Line A and 9 buses on Line B.
What’s the problem with this?

Better metrics should encourage “equity” by rewarding lower costs for disadvantaged user types, not incentivizing higher costs for advantaged users.

Standard deviation is still useful to evaluate the equity of a candidate solution, but it is not good to optimize for.
The same thing would happen if we used the Gini coefficient as our inequity metric.
An example of a “better” metric modifies standard deviation in two ways:

1. It replaces the “target” from the average cost $\bar{C}$ with a value $\hat{C}$ supplied by the decision-maker.
2. It only counts populations whose average cost **exceeds** the target value.

\[
I = \sqrt{(C_1 - \hat{C})^2 + (C_2 - \hat{C})^2}
\]
As an example, set the target $\hat{C}$ to be the average cost at the current allocation:
Now, the recommended solution is to put all 10 buses on Line A, which is the only logical decision.
EXAMPLE
Consider a fictitious “city” with 24 bus lines and 5 population groups. The ridership of each group is known for all lines.

The problem is to allocate the 340 buses among these lines with the dual aims of (1) minimizing waiting time and (2) doing so equitably among population types.
Different lines are used by each population type to varying degrees. The daily ridership values for each type are shown below.

<table>
<thead>
<tr>
<th>Type</th>
<th>Total ridership</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>297</td>
</tr>
<tr>
<td>2</td>
<td>978</td>
</tr>
<tr>
<td>3</td>
<td>8641</td>
</tr>
<tr>
<td>4</td>
<td>1392</td>
</tr>
<tr>
<td>5</td>
<td>966</td>
</tr>
</tbody>
</table>
This is the solution if the agency goal is to minimize total waiting time (ignoring differences in population type)

<table>
<thead>
<tr>
<th>Type</th>
<th>Total ridership</th>
<th>Avg. wait time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>297</td>
<td>32.4</td>
</tr>
<tr>
<td>2</td>
<td>978</td>
<td>22.4</td>
</tr>
<tr>
<td>3</td>
<td>8641</td>
<td>16.2</td>
</tr>
<tr>
<td>4</td>
<td>1392</td>
<td>23.9</td>
</tr>
<tr>
<td>5</td>
<td>966</td>
<td>19.1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>12274</td>
<td>18.2</td>
</tr>
</tbody>
</table>
The two objectives (minimize wait time and equity) can be combined

$$\min \sum_i f_i(x_i) + \gamma I$$

where $\gamma$ is a weighting showing the importance of equity relative to minimizing total wait time.
A few observations:

1. Starting from the “base” scenario, significant gains in equity can be obtained with only small increases in average waiting time.
2. The model cannot and should not say which combination of cost minimization and equity is right for a particular region; all it can do is illustrate tradeoffs.
CONCLUSIONS
Even though equity is an “intangible” concept there is still room for mathematical models.
There are subtleties in how inequity is measured which should be addressed. Are there “perverse incentives”? 

- Group 1
- Group 2

**Line A**
- High-crime neighborhood
- **CBD**
- **Line B** (“line to nowhere”)
In some cases, inequity can be reduced without increasing average costs by much.
Emerging data collection technologies can inform better “cost functions.”
Emerging data collection technologies can also support more detailed usage statistics by population type.
Summary:

1. There is a role for quantitative measures of equity...
2. ...but these measures must be studied to ensure they do not incentivize undesirable policies.
3. These metrics allow for tradeoffs comparisons between equity and other metrics.
4. New data collection technologies can support these quantitative methods.

QUESTIONS?