Transportation modeling and engineering

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What is a travel demand model?

- A mathematical model (think regression, but more complicated) that simulates how much travel will occur with different demographic and transport network scenarios

Why model transportation?

Why model transportation? Long-term

Why model transportation? Emissions

- The EPA defines six "criteria air pollutants" that are used to determine if an area is in compliance with federal air quality standards
  - Ozone, particulate matter ($\mathrm{PM}_{2.5}$ and PM_{10}), lead, carbon monoxide, sulfur dioxide, nitrogen dioxide
- Many of these come from transportation, and modeling future transportation plans helps plan to keep these within EPA limits
- In air quality non-attainment areas, additional modeling requirements apply

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The transportation modeling process

- All metropolitan planning organizations (MPOs) must produce a long range transportation plan (at least 20 years, but often 30-40)
  - The current CAMPO plan for the Triangle forecasts to 2055
- These plans include proposed changes to the transportation network and forecasted demographics and land use
- They forecast several key outcomes: vehicle miles traveled (VMT), congestion levels, mode splits (i.e. car/transit/walk/bike/other), and emissions

The workhorse of travel demand modeling: the four-step model

The four steps of the four-step model

Data sources for travel forecasting: the household travel survey

- The most important dataset for model development is a household travel survey
- Most regions conduct one every few years
- Households report their demographics and complete a *travel diary*—a list of all the trips they made during an assigned period (usually a day, but some agencies do multi-day surveys)
- GPS and smartphones have significantly reduced the respondent burden for travel diaries

Trip generation: the basics

- We need to know how many trips are produced in and attracted to each zone
- We are not forecasting at this point how many trips go from A to B, just:
  - how many trips leave A going anywhere (production)
  - how many trips go to B from anywhere (attraction)

Trip generation: types of trips

- Travel demand models classify trips into (at least) three types
  - Home-based work: trips between home and work (in either direction)
  - Home-based other: trips between home and non-work locations (in either direction)
  - Non-home-based: trips between non-home locations
- Many models will further divide into home-based shopping, school trips, school dropoff on work *tours*, etc.
  - A tour is a set of trips starting and ending at the same location

Trip generation methods: regression

- We develop a regression based on our travel survey to predict how many trips of a particular type a household will make
- We then apply this to all households in a zone, based on Census data or projections, to estimate how many trips will be produced in that zone
- Home-based trips are generally always considered to be produced at the home end, regardless of direction

Trip generation methods: regression example

This is the AM Peak home-based work regression from the model you'll use in the homework.

Characteristic	Beta[1]	SE	95% CI	p-value
(Intercept)	-0.01	0.017	-0.04, 0.03	0.7
vehicles	0.02**	0.008	0.01, 0.04	0.002
hhsize	-0.03***	0.007	-0.04, -0.01	<0.001
factor(income)				
0	—	—	—	
35000	0.02	0.014	-0.01, 0.04	0.2
75000	0.06**	0.020	0.02, 0.10	0.002
100000	0.05**	0.018	0.02, 0.09	0.005
HTRESDN	0.00	0.000	0.00, 0.00	>0.9
workers	0.35***	0.008	0.33, 0.36	<0.001
R^2	0.280			
Adjusted R^2	0.279			
Statistic	470			
p-value	<0.001			
No. Obs.	8,476			
Residual df	8,468			

[1] *p<0.05; **p<0.01; ***p<0.001

Abbreviations: CI = Confidence Interval, SE = Standard Error

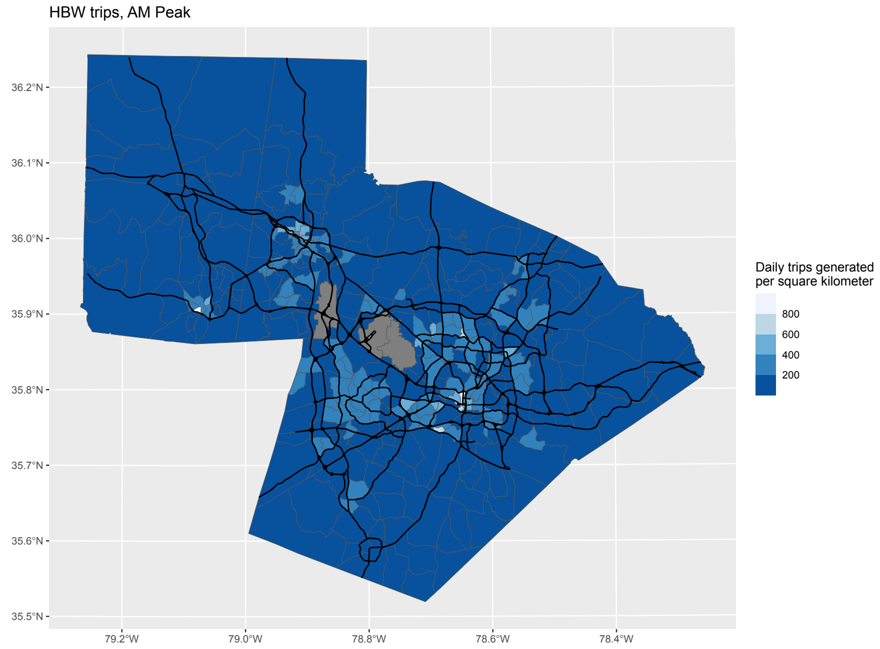
Trip generation methods: cross-classification

- Another (probably more common) method for trip generation modeling is *cross-classification*
- Here, you create a table dividing households or land uses by common characteristics, and just compute the mean trips for each type of trip and household/land use
- You then apply those rates to Census data or demographic forecasts to estimate the number of trips produced by each zone

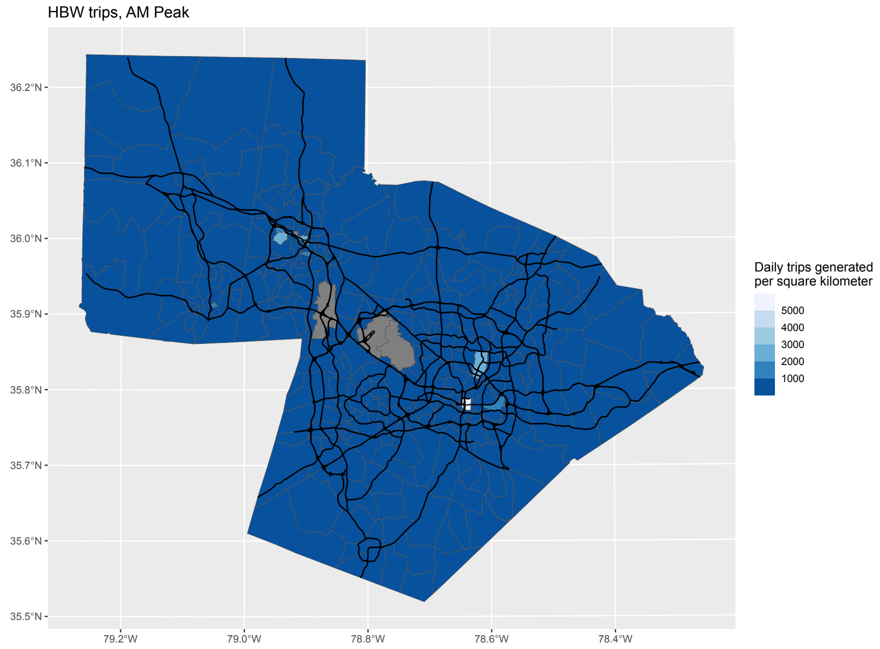
Trip generation methods: trip attractions

- For the attractions (non-home ends of trips), we can't use Census data or demographic forecasts, because those only tell use where people live
- Instead, we generally use employment counts (projected or from the US Census LODES dataset), or land uses
- If using employment, it's good to use employment in several sectors, in addition to total employment
  - e.g. retail or medical employment will attract more daily trips per job

Trip generation outputs



Production



Attraction

Trip generation: balancing

- We almost never have a matching number of productions and attractions, but of course this doesn't reflect the real world
- We're generally more confident in the quality of our estimations of trip productions, so we ~~fudge~~ adjust or *balance* the total attractions to match the total productions

Trip distribution

Trip distribution theory

$$\frac{m_1 m_2}{d^2}$$

- Anyone recognize this equation?

Trip distribution theory: conceptually

The gravity model

- One common method for trip distribution is the *gravity model*:

$$t_{ij} \propto \frac{p_i a_j}{d_{ij}^{\beta}}$$

where t_{ij} is the number of trips from i to j, p_i is the number of trips produced at i, a_j is the number of trips attracted by j, and d_{ij} the distance between i and j. $\propto$ means *proportional to*

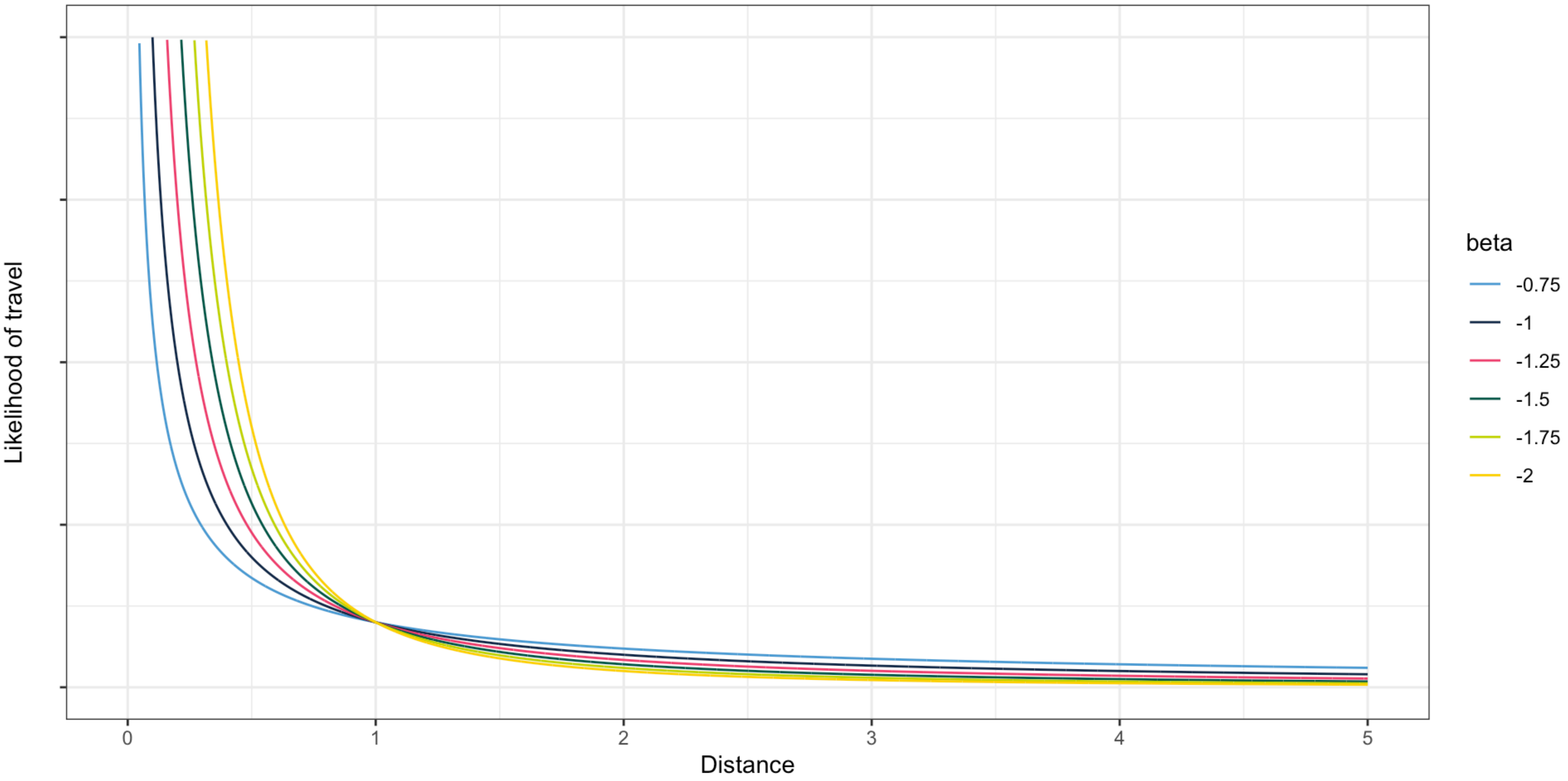
d_{ij}^{β} is called the *friction* of distance; β is estimated based on data

The gravity model

You may also see the gravity model written like this; in this case β is negative but otherwise it's equivalent

$$t_{ij} \propto p_a a_j d_{ij}^{\beta}$$

The β parameter



Other models: negative exponential

- You may also see negative exponential models
- These have a very slightly different functional form than gravity models

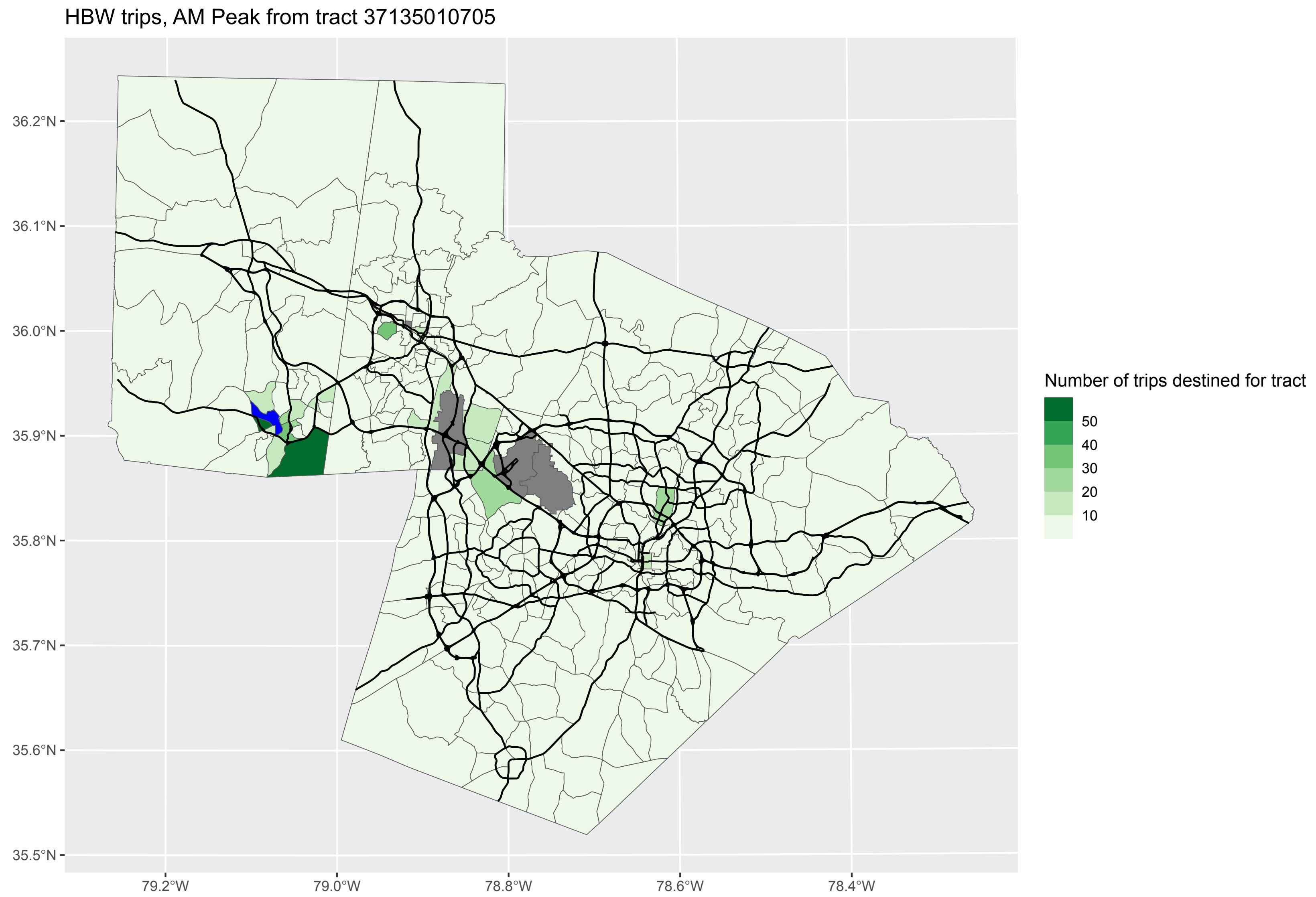
$$t_{ij} \propto p_i a_j e^{\beta d_{ij}}$$

Other models: intervening opportunities

- The intervening opportunities model bases estimates not on distance, but on how much is closer
- Conceptually, this makes a lot of sense: you might drive ten miles to a grocery store if there weren't any closer grocery stores
- But if you passed 15 grocery stores on the way, you'd be much less likely to travel that full ten miles
- Not used much, but probably should be used more

Generalized cost

Trip distribution with a gravity model



Mode choice

- We have now forecasted *how many* trips will occur between each zone at each time period, but we don’t know what mode they will use
- That is the role of the third step, mode choice
- Some MPOs skip this step if they have very little use of alternative modes in their region

Mode choice models

- Mode choice usually uses a *discrete choice* model, also known as a *random utility* model
- Most commonly, a *multinomial logit* or the slightly more complex *nested logit*
  - Also called *multinomial logistic regression* and *nested logistic regression*
- These are more advanced forms of regression where the dependent variable is categorical rather than continuous

The multinomial logit model

- The multinomial logit model expresses the value of each alternative as a *utility*
- The *utility functions* that determine this utility look like regular linear regression equations
- Whichever alternative has the highest utility is the one that will be chosen
- Each utility function has an error term, so which one is the highest is probabilistic not deterministic

The multinomial logit model: the math

A (very simple) mode choice model might look like:

$$\begin{aligned} U_{car} &= & \beta_t x_t + & & \epsilon \\ U_{transit} &= \alpha_{transit} + & \beta_t x_t + \beta_{i,transit} x_i + & & \epsilon \\ U_{bike} &= \alpha_{bike} + & \beta_t x_t + \beta_{i,bike} x_i + & & \epsilon \end{aligned}$$

where U is utility of each mode, t is travel time and i is income.

The multinomial logit model: probabilities

The probability of choosing any mode (in this case car) is:

$$p_{car} = P(U_{car} > \text{all other } U) = \frac{e^{U_{car}}}{e^{U_{car}} + e^{U_{bike}} + e^{U_{walk}} + e^{U_{transit}}}$$

(I'm not expecting you to remember this formula, I just want to walk through the math)

Interpreting a multinomial logit model: what you need to know as a planner

- You can read the utility functions just like linear regressions
- Anything that is associated with an increase in utility is associated with an increased likelihood of choosing that option, and a decreased likelihood of choosing the others
- Coefficients have standard errors, and you can do hypothesis tests and significance testing just like in linear regression

The mode choice step

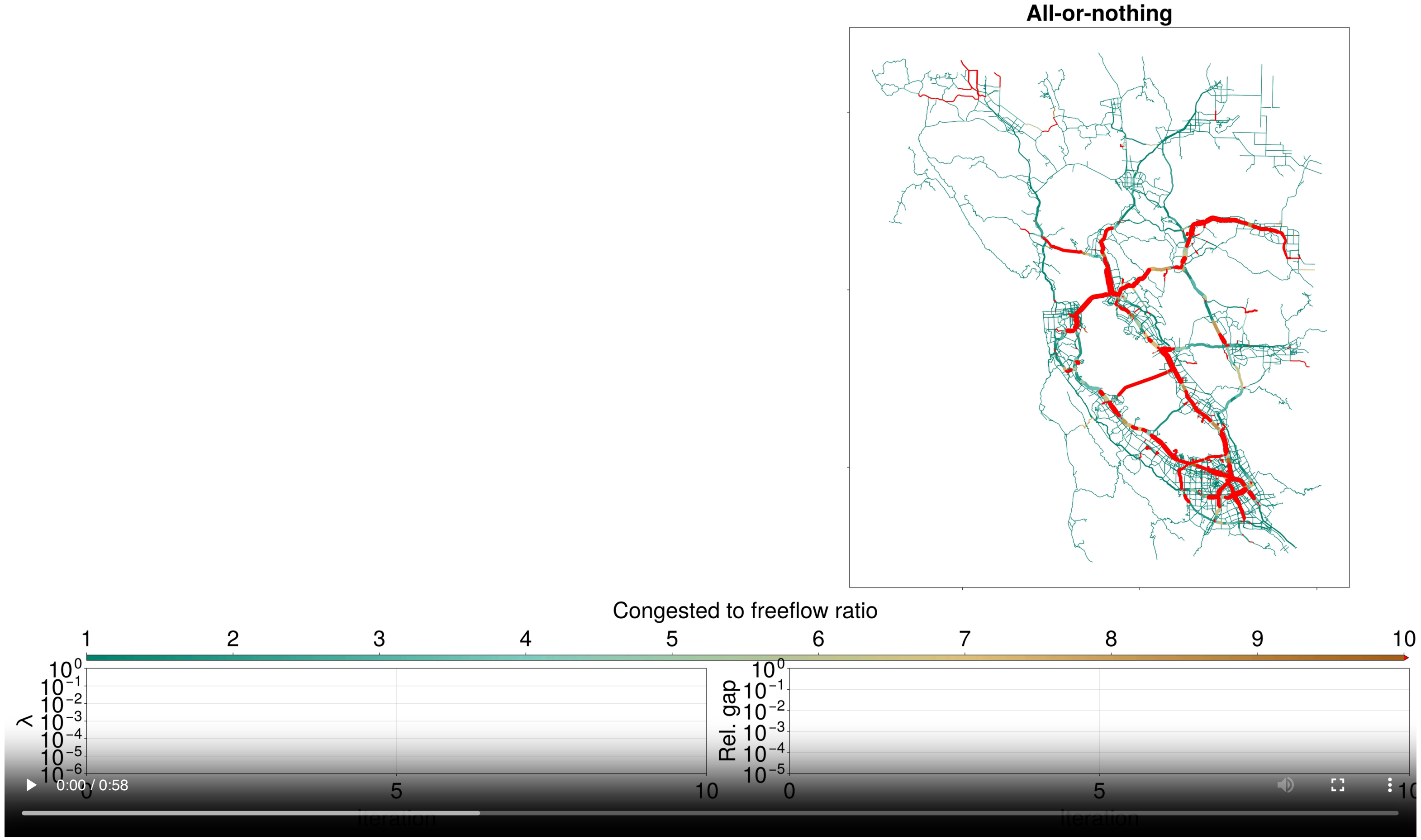
Network assignment/route choice

- The final step (phew!) is *network assignment*, aka *route choice*
- Often, the main outputs of interest are congestion and vehicle miles traveled (VMT)
- To calculate these, we need to know not only what the car trips were, but also what routes they took
- The network assignment step takes car trips between locations, and routes them on the network, accounting for the congestion caused by each trip
- Some agencies with significant transit ridership also do transit assignment

Network assignment/route choice: equilibrium

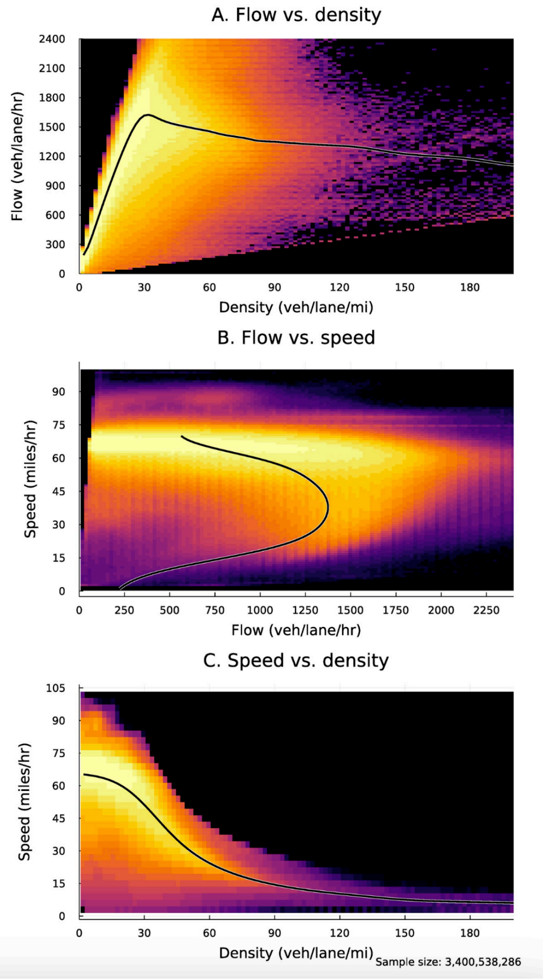
Network assignment/route choice: assigment

The Frank-Wolfe algorithm



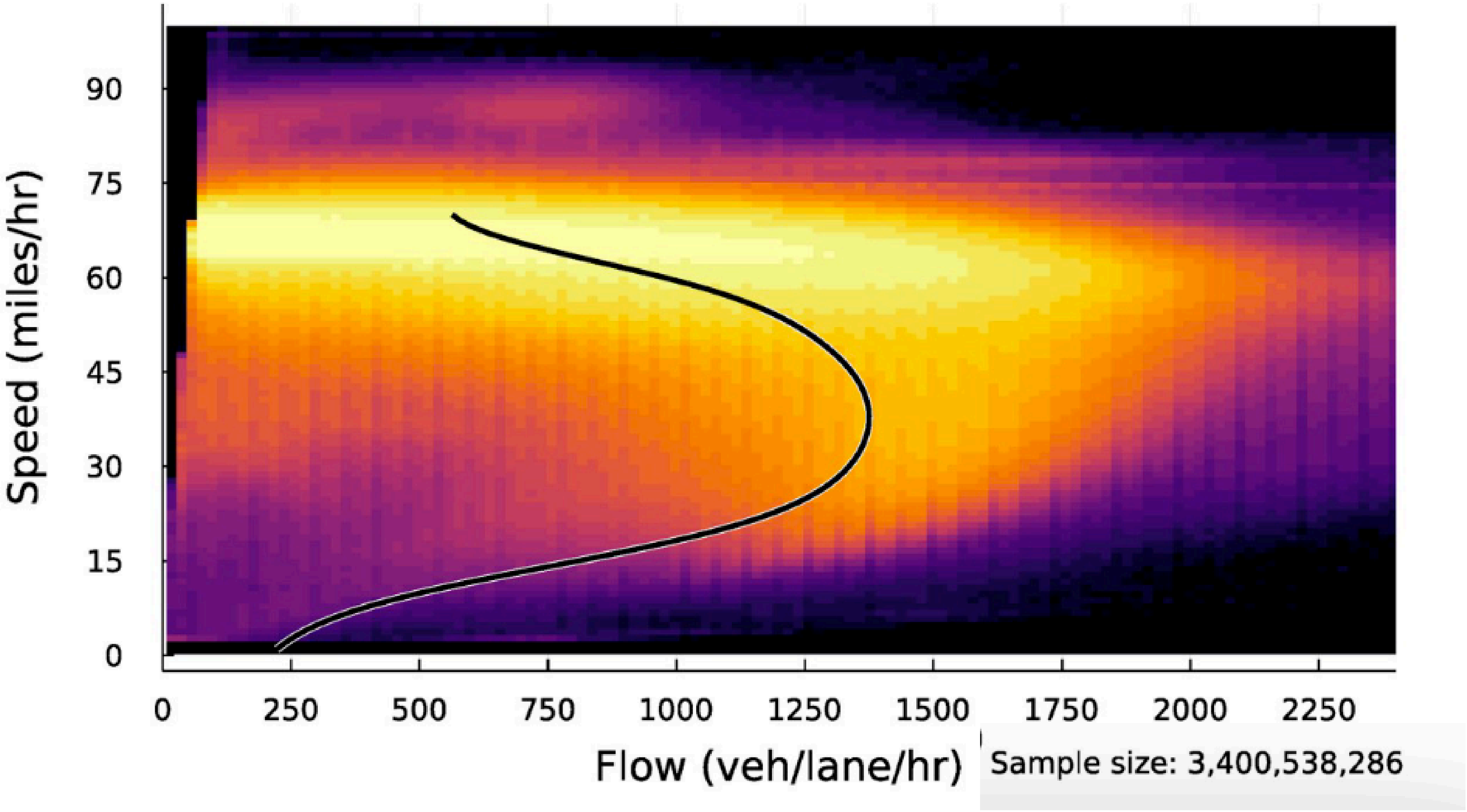
The fundamental diagrams

- How do we know how traffic volumes translate to congestion?



Bhagat-Conway and Zhang (2023)

The speed-flow diagram



Bhagat-Conway and Zhang (2023)

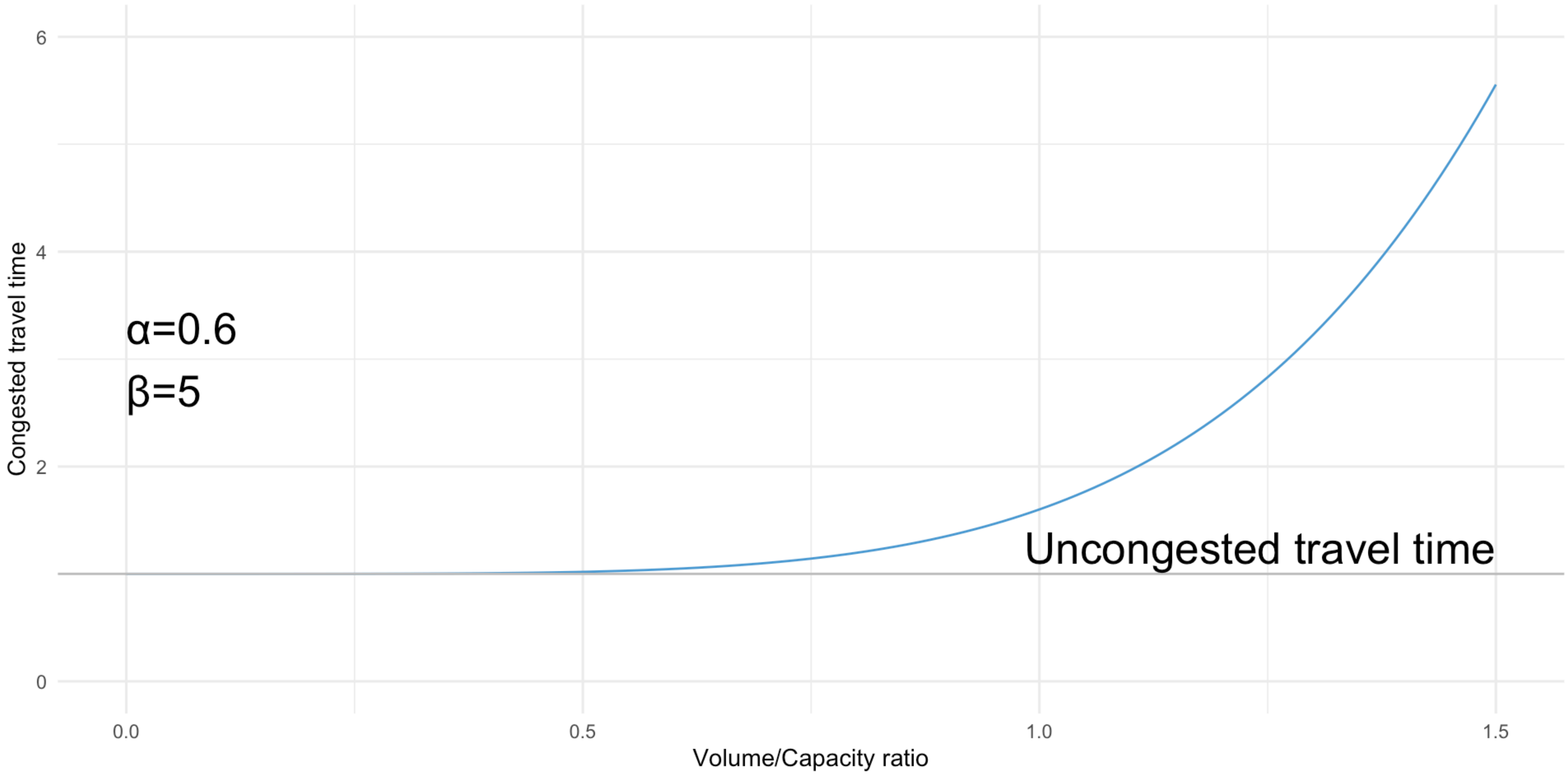
The Bureau of Public Roads function

The best-known formula for estimating congested travel time is the Bureau of Public Roads function, which estimates the congested travel time on a road segment as:

$$tt_{congested} = tt_{uncongested} \cdot \left(1 + \alpha\left(\frac{v}{c}\right)^{\beta}\right)$$

where tt is travel time, v is the forecast volume on the segment, c is the capacity of the segment, and α and β are parameters to estimate from data

The Bureau of Public Roads function



Additional components

- Emissions models
- External zones (traffic originating outside the region)
- Special generators/attractors: airports, universities, etc.

Criticisms of transportation modeling: land use is exogenous

- In most travel demand models, land use is treated as *exogenous*—i.e., taken as a given from projections or scenarios
- This means that you need to have a good land use forecast to get a good travel forecast
- Transportation affects land use just as land use affects transportation, so a really accurate model would model them jointly
- There is some progress on integrated land-use transportation models, but they are uncommon

Induced demand

Induced demand and the four-step model

Criticisms of the four step model: does not match how people actually make decisions about travel

Criticisms of modeling practice generally

- Many people criticize modeling as a *predict and provide* or *self-fulfilling prohecy*
- We model a future transportation network, build new highways based on the result, and then get the result we predicted, because we built it

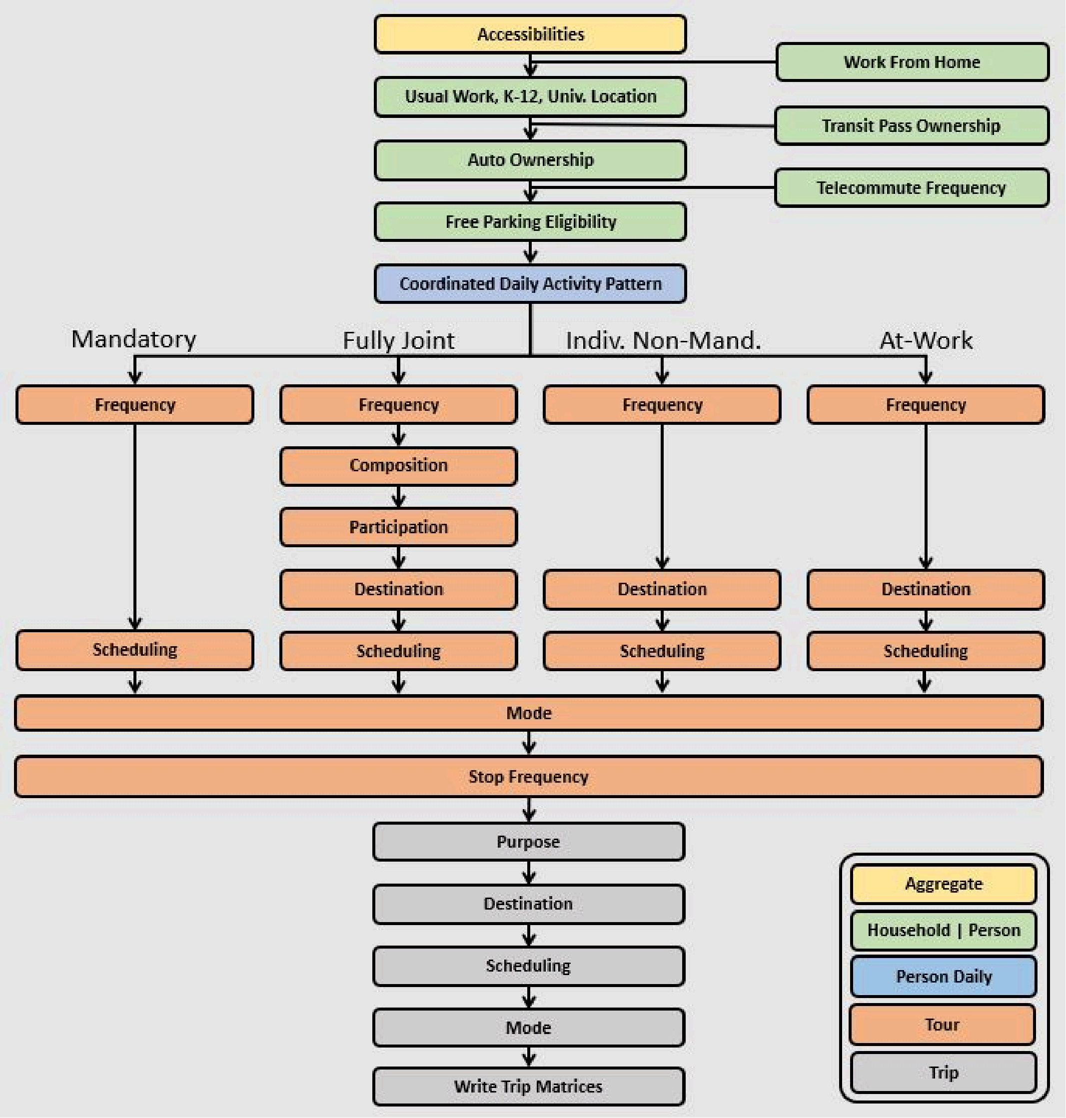
The next generation of travel demand models: activity based models

- Four-step models are still the most common travel demand model used, especially in smaller cities
- But the new state of the art is the *activity-based model*
- Activity based models are *disaggregate* models: instead of modeling total flows, they individually simulate the decisions of all the households in the region

Activity based models

- They are computationally complex, but in many ways much more intuitive than four step models
- First, you generate a *synthetic population*: data on each household in the region
  - Since we can't actually collect this, we use Census data to create fake households that in aggregate resemble the actual population
- The core of the model is a set of dozens of regressions, modeling a slew of household- and person-level decisions
- e.g. destination choice, departure time choice, mode choice, etc.
- Each individual or "agent" gets their own schedule of where they're going when
- These are aggregated to produce outputs

Activity-based model components



Components of ActivitySim

Transportation engineering

Design guides: MUTCD, HCM, Green Book, Trip Generation Manual, NACTO guides

- Traffic engineering tends to be much more formulaic than planning
- There are a myriad of design guides that engineers use for different aspects of planning
- This can lead to clashes between engineers and planners

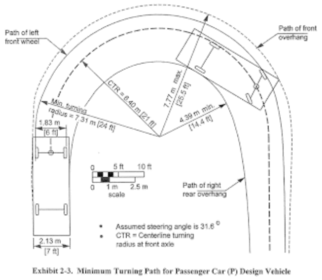
Roadway geometry

- The design and layout of roadways is *heavily* dependent on design guidance from a number of standards agencies
  - AASHTO
  - NACTO
- Deviating from these guidelines is often difficult, and a major source of friction between planners and engineers

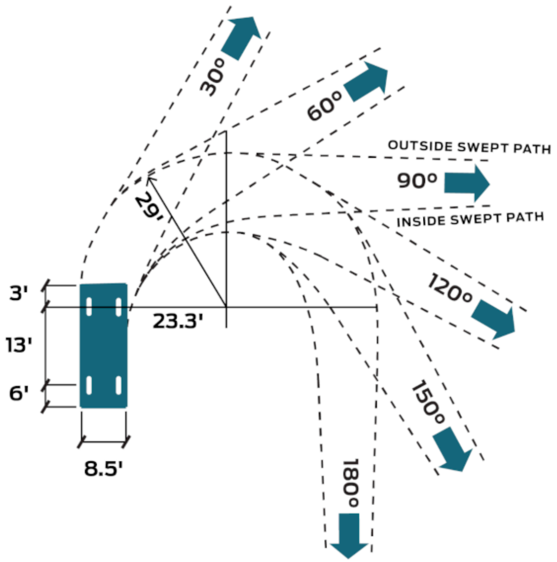
Design vehicles, control vehicles, and managed vehicles

- One of the key inputs to the geometric design of roadways is the selection of the *design vehicle*
- This is the largest vehicle regularly expected to use the roadway, from a standardized list of vehicles in the AASHTO green book
- The selection of this vehicle has a very significant effect on the design of the roadway, including lane widths but especially turn radii

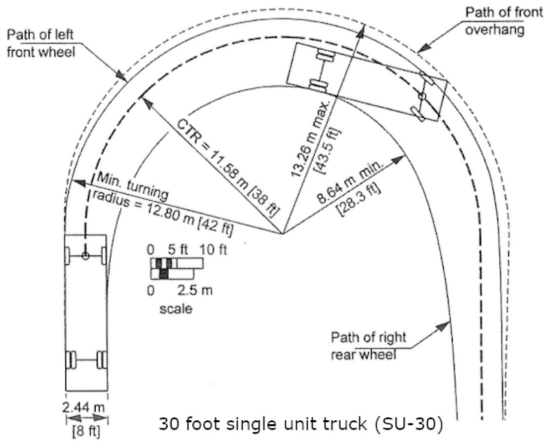
Design vehicles and turning templates



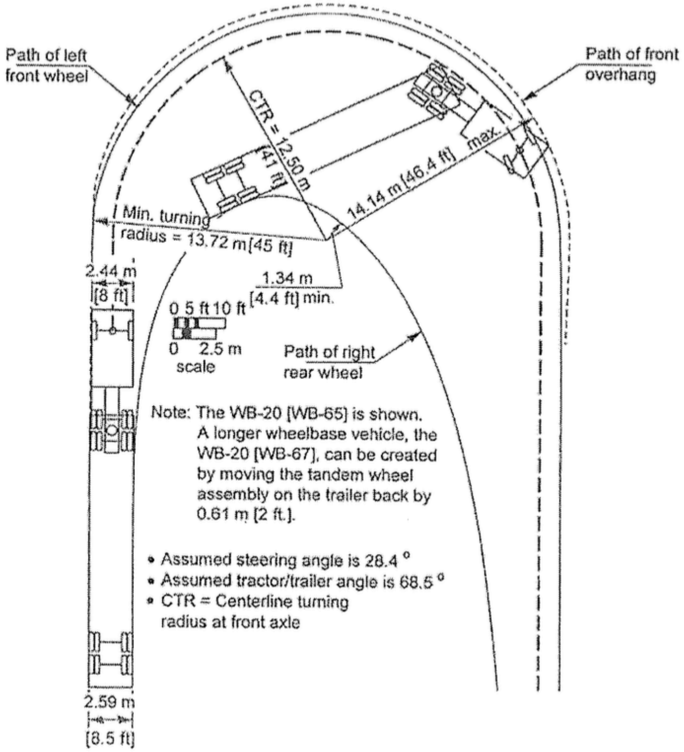
Passenger car (P)



Delivery van (DL-23)



30 foot single unit truck (SU-30)



Semi truck with 53-foot trailer (WB-65/WB-67)

AASHTO Green Book, NACTO

Design vehicles and turning radii

- The larger the design vehicle, the larger the turning radius must be
- The larger the turning radius, the faster smaller vehicles will travel around the turn

Design vehicles in North Carolina

From the NCDOT roadway design manual (all state owned roads, emphasis mine)

> North Carolina state law G.S. 20-115.1 allows vehicles with WB-62 and WB-62FL design characteristics on all North Carolina primary routes. Abide by the following guidance when selecting the design vehicle on all state routes.
>
> - **WB-62FL** shall be the standard design vehicle for all primary routes in the state and should be considered on industrialized streets that carry high volumes of truck traffic or provide local access for large trucks. Primary routes are defined as any interstate, US, or North Carolina route.
> - **WB-62** shall be the standard design vehicle for all other routes, with context sensitive considerations given to constrained corridors.
>
> Under special circumstances, the standard design vehicle may be larger than a WB-62FL when the project is in the vicinity of specialized trucking facilities or smaller than a WB-62 due to project constraints. If the standard design vehicle cannot be accommodated, discuss the project specific constraints with the project team and Division and develop documentation of the decision-making process. At minimum, accommodating a Conventional School Bus (S-BUS 36) should be considered. Coordinate with the local school system to determine if a Large School Bus (S-BUS 40) should be specified in lieu of the S-BUS 36.

Introducing control vehicles

- The “control vehicle” is a newer concept, responding to the idea that we don’t need to design all our street for giant trucks
- The control vehicle is the largest vehicle that could get down the street, even if that meant crossing the center line, driving over some curbs, making a three-point turn, etc.
- E.g. we know that moving trucks may need to go down residential streets, but it doesn’t need to be easy

A WB-62 making a tight turn, East Boston, MA

The managed vehicle

- The most common vehicle that uses a street
- The intersection should be designed to manage the turning speed of this vehicle
  - e.g. keep turning speeds below 10mph at protected intersections

Mountable curbs and aprons: have your radius and eat it too

Design speeds and speed limits

- Every road has a “design speed”
- This is the speed that the road is designed for, often higher than the speed limit
- Speed limits are usually set based on the 85th percentile speed

Risk compensation

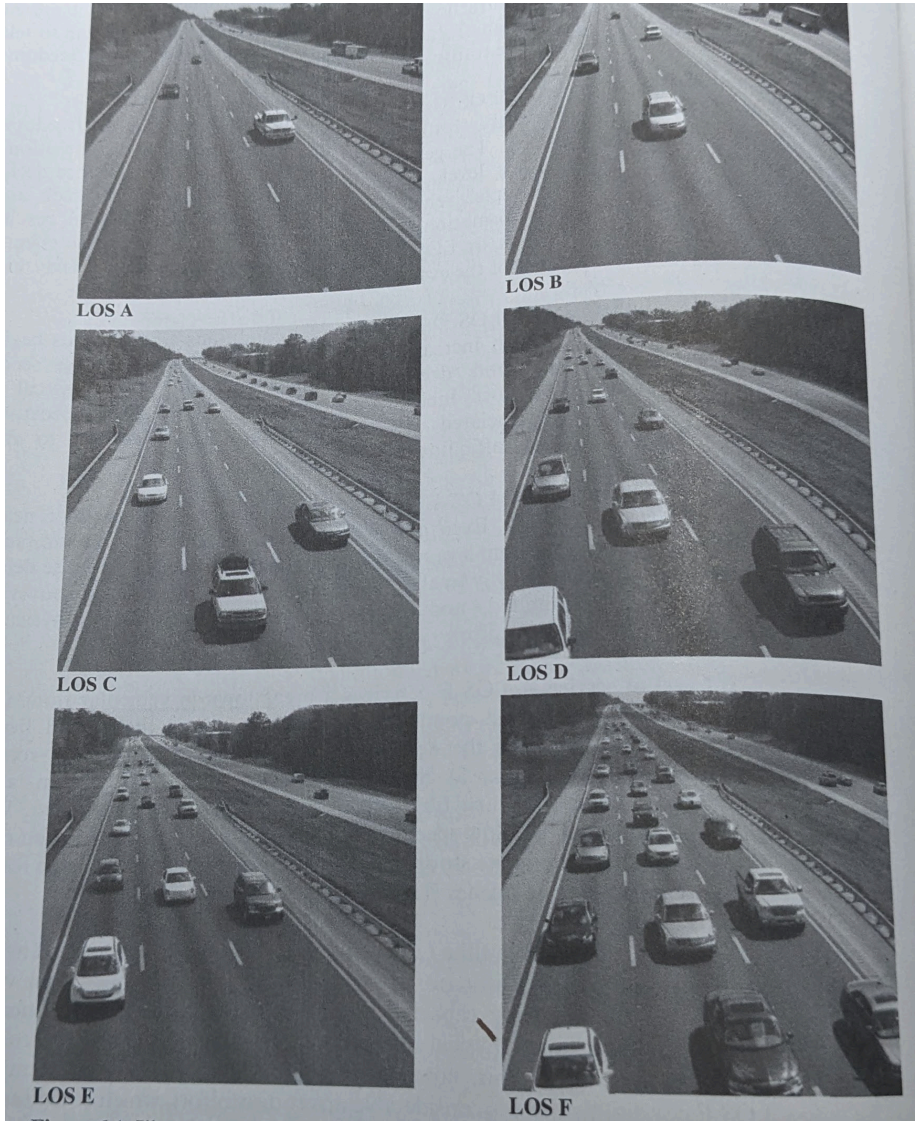
The Tullock spike

- Gordon Tullock proposed the best way to improve road safety would be to mount a dagger in the center of every steering wheel
- This would make people drive so carefully crashes would be a thing of the past

Highway capacity analysis

- There are complex formulae for determining the capacity of a roadway, based on roadway design, driver behavior, signalization, access (entrances/exits/weaving), car/truck traffic composition, etc.
- Once capacity is determined, it is used to compute a *level of service* from A to F

Level of service



Mannering and Washburn (2020)

Level of service: intersections

- There is also an intersection LOS, based on seconds of delay for the average vehicle

LOS F ≠ failure

- Engineering guidance suggests maintaining at or above LOS D
- In urban areas, this is not going to be possible
- You will ~~sometimes~~ always get pushback on projects that worsen LOS, but it's important to account for project context
- LOS F shouldn't be viewed as a failure of the system, but as a measurement of delay
- The most economically productive places (e.g. Manhattan) often have very low LOS
- Some places are moving away from LOS for this reason
- Similarly, it's okay if volume is sometimes larger than capacity; this is inevitable in urban areas

Traffic counts

- Traffic counts are a primary data source for traffic engineering
- They can be manual, temporary and automated, or permanent and automated
- They are used to determine *annual average daily traffic* (AADT), which is the basis of many other traffic engineering concepts

Design volume

- Projected volumes are often based on demand during a “design hour”
- This is often the 30th or 50th busiest hour of the year
- The design hour volume is often estimated by multiplying the AADT by a factor known as the K-factor
  - There is evidence that this K-factor is getting smaller post-pandemic *(Bhagat-Conway and Zhang 2023)*

The *Manual on Uniform Traffic Control Devices* (MUTCD)

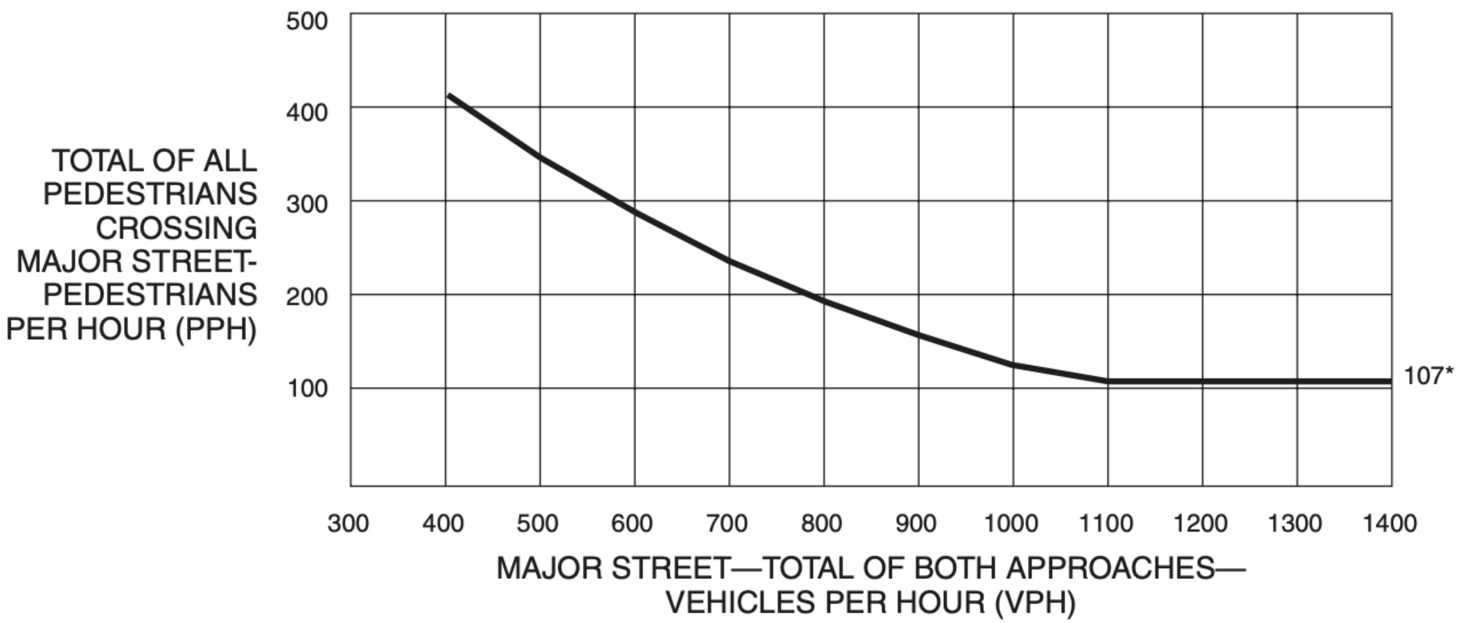
- This is an FHWA publication that regulates the design and placement of signs, signals, and pavement markings
- It provides a consistent set of signs and signals that drivers can expect to see
- Deviating from these can be difficult
  - e.g. the new HAWK crossing signals took a while to be accepted

Signal warrants

- The MUTCD has a list of “warrants” for when a signal is justified, based on
  - Vehicular volume
  - Pedestrian volume
  - School crossing
  - Crash experience
  - Traffic flow
  - Railway grade crossings
- Not absolute rules, but strong suggestions

The pedestrian warrant

Figure 4C-5. Warrant 4, Pedestrian Four-Hour Volume



*Note: 107 pph applies as the lower threshold volume.

2009 MUTCD, rev. 3

Intersection control evaluation

- Intersection control evaluation is a systematic, multi-step process to consider the benefits and costs of traffic control devices
- Considers safety, capacity, and community context - though how is left up to implementers
- Used by 15 state DOTs, including NC

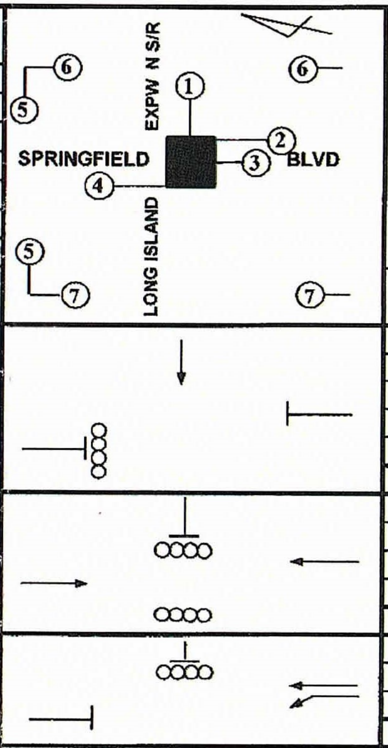
Signal timing

- Signal timing is a big part of traffic engineering
- The main concepts to remember are *saturation flow*, *cycle length*, *lost time* and *effective red/green times*
- The *saturation flow* is how much flow could occur from one direction, if that direction always had a green light
- The *lost time* is time that is lost due to acceleration, clearance times (when the signal is red all ways), etc.
- The *effective green time* is how long traffic coming from a direction is moving unimpeded
  - It is not the same as the green time, because of the lost time
- A phase is a single set of movements
- Cycle length is the amount of time it takes for the signal to complete all phases
- The shorter the cycle length, the longer the lost time

Traffic signal timing cards

	1	2	3	4	5	6	7	8	9
	R	R	R	R	DW	DW	DW		
	A	A	A	A	WK	WK	WK		
	G	G	G	G					
			←G						
L/S #	1	2	3	4	5	6	5Y/6Y		
NEMA	1	OL1 (2+3)	3	2	1P	POL1 (2+3)	2P		

	1	2	3	4	5	6	7	8	9	1: MON-FRI 05:00-10:00	2: MON-FRI 10:00-13:15 WEEKEND 08:30-13:15	3: MON-FRI 13:15-20:30	4: MON-FRI 00:00-05:00 WEEKEND 00:00-05:00	5: MON-FRI 20:30-00:00 WEEKEND 05:00-08:30 20:30-00:00	6: WEEKEND 13:15-20:30
										120 SEC	90 SEC	90 SEC	90 SEC	90 SEC	90 SEC
PHASE A	G	R	R	R	WK	DW	DW			46	26	26	26	26	26
SPARE	G	R	R	R	WK	DW	DW			2	2	2	2	2	2
PED CL	G	R	R	R	FLDW	DW	DW			12	12	12	12	12	12
VEH CL	A	R	R	R	DW	DW	DW			3	3	3	3	3	3
VEH CL	R	R	R	R	DW	DW	DW			2	2	2	2	2	2
										65	45	45	45	45	45
PHASE B	R	G	G	G	DW	WK	WK			12	7	7	7	7	7
PED CL	R	G	G	G	DW	WK	FLDW			13	13	13	13	13	13
VEH CL	R	G	G	A	DW	WK	DW			3	3	3	3	3	3
VEH CL	R	G	G	R	DW	WK	DW			2	2	2	2	2	2
										30	25	25	25	25	25
PHASE C	R	G	G/←G	R	DW	FLDW	DW			20	15	15	15	15	15
VEH CL	R	A	A	R	DW	DW	DW			3	3	3	3	3	3
VEH CL	R	R	R	R	DW	DW	DW			2	2	2	2	2	2
										25	20	20	20	20	20



OFFSET					
53	21	37	68	37	15

CITY OF NEW YORK
BUREAU OF TRAFFIC OPERATIONS
34-02 Queens Blvd. Long Island City, NY 11101

DATE	BY	REVISIONS
07/02/13	YG	Modify timing

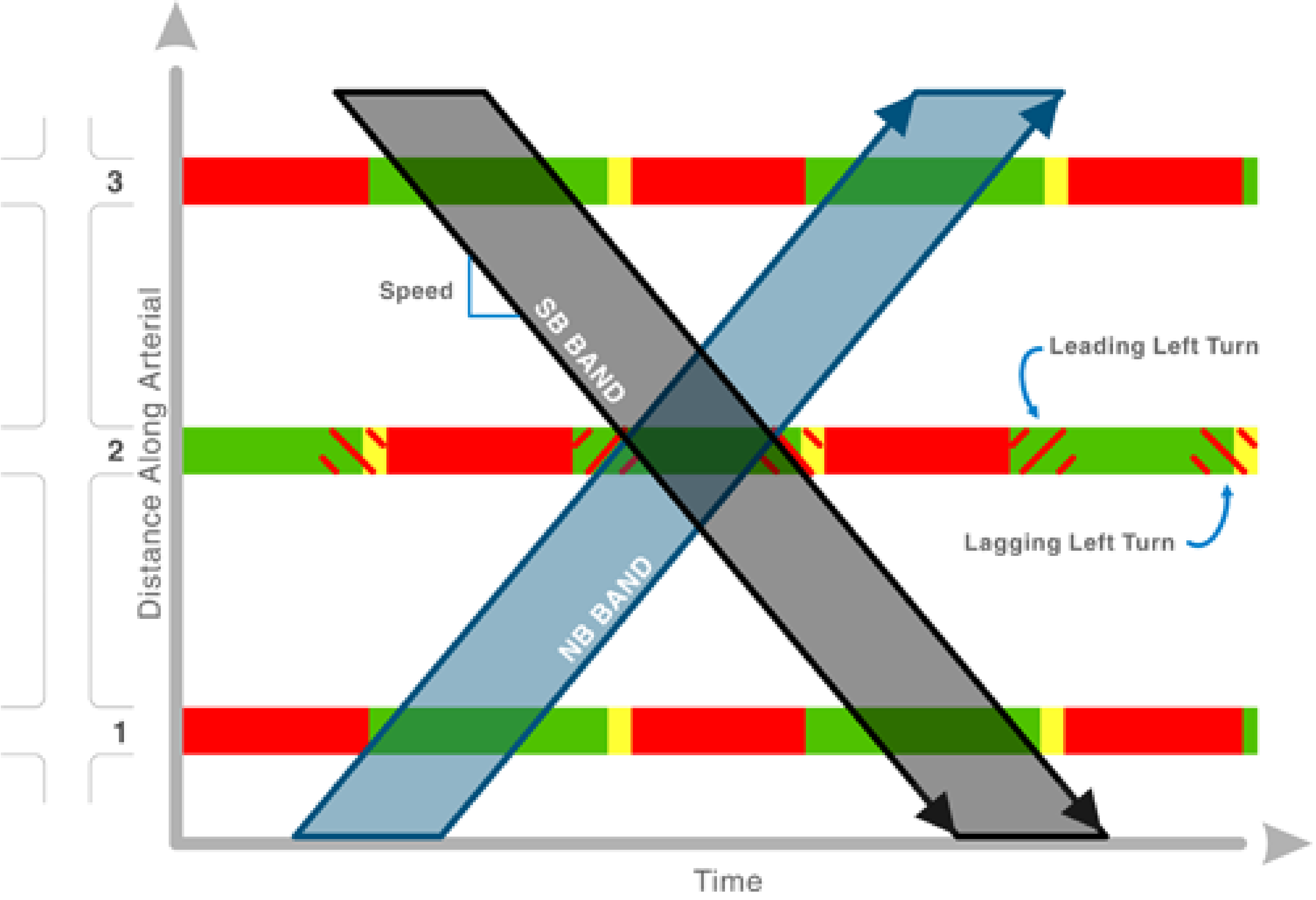
Channel "7" I/O Mapping
Don't use Default I/O mapping
Use "ALT" I/O mapping
NOTES: NON-ACTUATED
PC = 3.0 FT/SEC
CABINET TYPE: ASTC-6
CABINET ADDRESS: 6F78
CONTROLLER # 1
INTERVAL PROGRAM

LIE N S/R @ SPRINGFIELD BOULEVARD

Prep. Y.GIRGIS Date 07-02-13
Appr. N.Ibrahim Date 07-02-13

Dian Mao/NYCDOT

Time-space diagrams



FHWA

The tension between planners and engineers

- There is often tension between engineers and planners
- Frequently, this stems from the more formulaic nature of engineering
- Some of the engineering formulae certainly do need changing, but understanding the professional environment in which engineers operate is helpful

© xkcd

References

Bhagat-Conway, Matthew Wigginton, and Sam Zhang. 2023. "Rush Hour-and-a-Half: Traffic Is Spreading Out Post-Lockdown." *PLoS One*.
Mannering, Fred L, and Scott S Washburn. 2020. *Principles of Highway Engineering and Traffic Analysis*. 7th ed. Hoboken, NJ: Wiley.

Thanks to Kush Bhagat for insights on transportation engineering