CITY AND REGIONAL PLANNING 776

A Corridor Framework for Modal Comparisons

Philip A. Viton

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1 Introduction

What is the best way to move people around an urban area? This is by no means a straightforward question, but one way to approach it is to ask: which mode uses up the fewest of society's scarce resources? That is the approach we adopt here.

Now, there are two difficulties with this approach. The first is that transportation is a bit unusual: the scarce resources that are used in making a trip consist not only of the resources contributed by the mode's operator (gasoline, oil, vehicles, etc) but also in resources contributed by the *traveller* (user), typically in the form of time. In order to be accurate about "resources used up" it is vital that we take account of user-contributed resources as well as operator-contributed ones.

The second difficulty is more generic: we face a *units* problem. How are we to compare modes which use (say) less of one resource and more of another? This is a classic applies-and-oranges problem. The solution is to convert everything to a common equivalent unit. Most of the time, the most convenient unit is *cost*, on the view that market prices measure the (marginal) value of a resource to society, ie its *opportunity cost*, what society gives up by using the resource *here* rather than in its next-best setting. When this is done we arrive at the concept of the *comparative costs* of trip-making by various modes.

One important difficulty with comparative costs arises when some resource(s) do not have (market) prices. That is certainly true of the user-contributed time component of trip-making, which we can call *user costs.* So we need to find a way to convert time spent trip-making into an equivalent amount of money. For the moment we shall take the easy way of doing this: we will assume that we know a user's *value of time*, which performs precisely this function. So we will have: user cost = [time spent] × [value of time].

That leaves the task of determining the amount of time spent by a user in making a trip on a given mode. It is often convenient to consider this in the context of a given trip (ie trip purpose) made in a specific spatial setting. In this note, I sketch how that could be done for work trips (typically in the peak period) in a transportation corridor connecting origins and destinations. It is based on work by **?**, also used by **?** and many others. We consider the trip of a single average individual (the commuter) between his or her home, in a residential area, and the individual's work location, in a CBD. Then we interpret the various links of the trip in terms of the mode being used for the trip. Note that it is easy to re-interpret the trip as a shopping trip by thinking of the CBD as a shopping center.

2 Spatial layout

The spatial layout of journey-to-work trips is shown in Figure 1. There is a circular residential area of radius r miles. Within the residential area, local roads are laid out along the radii, as shown in the figure by the dashed lines. We shall not worry about just *where* the local roads are: in effect, we shall assume that there is a local road going through any point of interest. We also assume a network of circumferential streets connecting the radial roads: again, we will not worry about just how many of these there are. (The reason is that for almost any reasonable case, the changes which would result from more detail are very small, and the complicated formalism necessary is almost certainly not worth the trouble).

All destinations are taken to be within a 1-mile square CBD. Within the CBD, we assume a grid pattern of roads, an assumption once again made for convenience, and not likely, in almost any reasonable case, to have a significant effect on our results.

The residential area and the CBD are connected by a larger road, which we can think of as either a major arterial or a limited-access expressway. In the latter case, we assume that point C represents the only feasible expressway entrance for people living in the residential area. The distance between C and the edge of the CBD (point D) is L miles, often called the "linehaul distance".

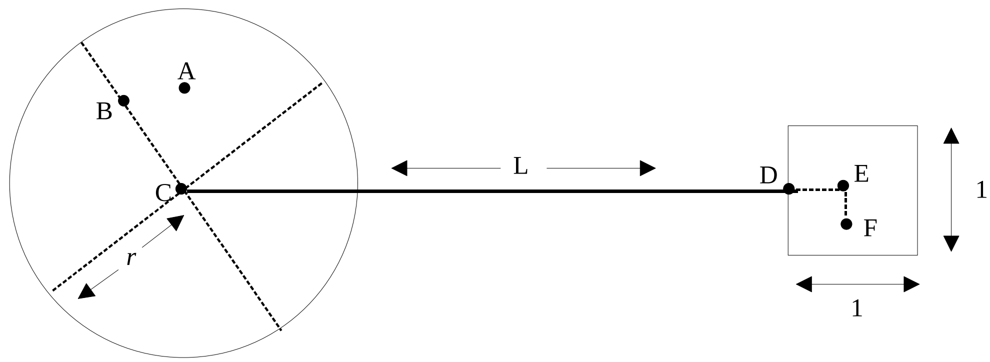

Figure 1: Spatial Corridor Layout

3 Trip making

We now describe how trips occur, when our average traveller uses various modes to get to work. We assume that the average traveller's origin is at point A, at the mid-point of some radius in the residential area. The point is that some travellers will be located further towards the edge, while others will be closer to the center: we're implicitly assuming that everything averages out to the mid-point case. Clearly, if you don't like that assumption, you could repeat the analysis for various locations along one of the radii. We also assume that the destination is at F in the residential area.

3.1 Auto trips

We model the commuter making a non-carpool trip between A and F. In this case the trip components are as follows:

- The commuter drives along one of the residential streets from A to C.
- Then she drives along the larger road — at arterial or freeway speeds, which will typically be faster than the speed possible in the residential area — from C to D.
- She drives at downtown speeds from D to E, which we can think of as a parking lot.

- Finally, she walks from E to her destination at F.

We can modify this structure to allow for carpooling, for example, by adding a "circuity time" to the portion of the trip in the residential area, to allow for the fact that the commuter — who we assume is the driver of the car — incurs additional time to pick up the passengers.

3.2 Bus transit trips

Trips by bus transit are a bit more complicated.

- The commuter must first get from her origin at A to the location of the nearest bus stop, which we assume is at B (we will be more explicit about this later). An additional consideration is *how* she gets from A to B: we can think of at least three ways: walking; driving, where she leaves the car at B to await her return, known as park-n-ride; or where she is driven — typically by her spouse — to the bust stop the car drops her off, and is available for other activities during the day: this is often called kiss-n-ride.
- Once at B, she waits for the next scheduled bus to arrive.
- She boards the bus, which travels along residential streets to C
- The bus then travels at typically higher speeds from C to D
- When the bus reaches the edge of the CBD (at D) it slows down, travelling at city-street speeds (note that these may differ from the city-street speeds for autos, because of stops) to F via E. Note that we are assuming that the bus drops our commuter off at her destination; this is typically an acceptable assumption, but if not, you could easily model the case where the commuter gets off at E and walks to F.

This models two types of bus transit trips, depending on the nature of the road connecting C and D: when this road is an arterial we have a standard transit trip; when it is a freeway we have an express-bus trip.

4 Rail trips

Here we imagine that we have a rail line — which could be a commuter-rail or light-rail line — laid out parallel to the arterial/expressway connecting C and D. Note that we assume that the length of this line is the same as the length of the road: this is probably harmless, at least from the point of view of the commuter, since we can adjust the speeds to take account of different trip lengths.

In this framework, trips proceed as follows:

- First, the commuter must get to the rail stop at C. We can imagine at least three ways this can happen:
  - The commuter walks along residential streets from A to C
  - The commuter drives or is driven (park-n-ride or kiss-n-ride) from A to C
  - The commuter uses another transit mode, say bus, to get to C. An interesting case is where the other mode is a dedicated mode — its only task is to feed people in to the rail mode. Call this the "connector" or "feeder" system.
- In the third case — transit access — the trip begins in the usual way:
  - The commuter gets to the nearest bus stop, which we take to be B. Note that this may or may not be the same stop as in the bus-transit case: for example, there may be a dedicated feeder bus system, devoted only to getting people to the rail stop at C. Again, we can discuss how this portion of the trip takes places: walk, park-n-ride, kiss-n-ride, etc.
  - The commuter waits for the next bus. Again, the wait time need not be the same as the standard-bus-transit wait if there is a feeder bus system.
  - The commuter then travels at bus speeds from B to C.
- In any case, once the commuter gets to C, there is a *transfer time* while she switches from her access mode to the rail mode. (This would include time to purchase the rail ticket and to walk onto the rail platform).
- The commuter then waits at C for the next train to arrive.

- She travels at rail speeds from C to F. Note that one advantage of rail modes is that they can typically keep up the same speeds whether they're in the CBD or not (though this may need to be modified by more frequent stops). Also, we assume that transit gets her closer to her final diestination than auto does.

4.1 Transit level of service

From the perspective of the commuter, transit's level of service has three components (besides the cost or fare): access time, wait-time and in-vehicle time. The in-vehicle time is completely determined by the distances involved, plus the speeds at which the transit vehicle moves along the relevant component of its route; so we turn to the other two.

It turns out that under some reasonable assumptions, access and wait times can be determined if we characterize transit's level of service in terms of two operator-determined characteristics. These are: the number of equally spaced radial routes in the residential area, and the transit vehicle *headway*, that is, the time between successive vehicles on each route. If we know how many equally spaced routes there are, then we can easily figure out how far the average commuter must travel to get to the nearest route: it's half the distance between routes. And if we know the system headway, and if we are prepared to assume that people arrive randomly at each bus stop, then the average wait is given by the engineering rule-of-thumb: wait equals half the headway.

It is worth taking a moment to consider the assumption of random arrivals. It would not be reasonable if transit operated at relatively long headways: in this case there is an incentive for commuters to learn the schedules, and time their arrivals to be just before the vehicle will probably get there. Thus, if we know that buses arrive every hour on the hour (headway = 1 hour) then we certainly do *not* expect that the average wait will be half the headway, or 30 minutes. Clearly, commuters will try to arrive just before the bus is expected, and the average wait will be on the order of ten minutes or less (depending on just how variable the arrival times are). But for our case — journey to work in metropolitan areas — it is probably acceptable to assume that headways are sufficiently small not to make it worthwhile trying to time one's arrival at the transit stop.

5 A notation

We now introduce a notation for the trips just discussed. We will not try to capture all complications and variations of the trips; it should be apparent how you can modify all this to describe more complicated trips.

5.1 Distances

We are considering a CBD which is 1-mile square. To make things simple, we shall fix a couple of the distances at the end of the trip. (It is of course easy to modify these assumptions: the consensus is that except in extreme cases, any such modifications will have very little impact on the answers we come up with). The distances are shown in the following table:

Component	**Link**	**Distance**
Residential radius		r
Linehaul distance	CD	L
Origin distance	AC	$r/2$
CBD vehicle distance	DE	$1/2$
CBD walk distance	EF	$1/4$

5.2 Speeds

The only complication here is that each mode will typically attain different speeds along different portions of the route, so we just index speeds by the mode we are considering: a for autos, b for buses and t ("train") for the rail mode.

Component	**Auto**	**Bus**	**Rail**
In residential area	s_{ar}	s_{br}	–
Linehaul	s_{al}	s_{bl}	s_{tl}
Along CBD streets	s_{ac}	s_{bc}	(s_{tl})
Commuter walk speeds	s_w	s_w	s_w

Note that rail speeds "along city streets" are the same as rail linehaul speeds: we are in effect assuming that rail moves on a separate guideway.

5.3 Values of time

As we will see, much of our evaluation work will be based on commuter's willingness-to-pay to avoid spending time making trips. We refer to these as "values of time"; how they are to be ascertained empirically will be discussed later. For now, we just introduce some notation.

Component	Auto	Bus	Rail
Walk	v_w	v_w	v_w
Wait		v_{wwb}	v_{wwt}
In–vehicle	v_{ia}	v_{ib}	v_{it}
Transfer		v_{tt}	v_{tt}

5.4 Transit level of service

We have argued that transit's level of service can be described by two operator-determined characteristics.

Characteristic	Standard Bus	Feeder Bus	Rail
No. equally spaces residential routes	R_c	R_f	–
Headway	Ψ_b	Ψ_f	Ψ_t

Note that we are assuming that the rail mode operates on a fixed guideway, so that the issue of the number of routes does not arise.

The link between the level-of-service measures and the times experienced by the commuter is given by the following table, where we use R to mean the number of equally spaced residential routes, and Ψ for the headway of any mode.

Component	Time
Access	$\pi r/2s$
Wait	$\Psi/2$

where s is the access speed (for example s_w is access is by walking) and r is the radius of the residential area. Remember that the wait time results is valid only for the case of random arrivals at a bus stop (as argued above, this is reasonable for peak-period commute trips; but it may not be valid at other times).

6 Value of trip-making time components

We now assemble symbolic expressions for the times taken by the various trip components, and their valuation by our average individual commuter. Remember that distance = speed × time, so that time is distance / speed; and the value of the time component will be the time multiplied by the appropriate value of time.

6.1 Auto trips

In this case we study non-carpool trips.

Component	**Description**	**Time**	**Value**
$A \to C$	IVTT — res. area	$r/2s_{ar}$	$v_{ia}r/2s_{ar}$
$C \to D$	IVTT — linehaul	L/s_{al}	$v_{ia}L/s_{al}$
$D \to E$	IVTT — CBD	$1/2s_{ac}$	$v_{ia}/2s_{ac}$
$E \to F$	Walk	$1/4s_w$	$v_w/4s_w$

6.2 Bus transit

We study bus transit with walk access only. It should be apparent how to modify the expressions to take account of other access modes.

Component	**Description**	**Time**	**Value**
$A \to B$	Access	$\pi r/2R_b 2s_w$	$v_w \pi r/2R_b s_w$
Wait at B	Wait	$\Psi_b/2$	$v_{wwb}\Psi_b/2$
$B \to C$	IVTT — res. area	$r/2s_{br}$	$v_{ib}r/2s_{br}$
$C \to D$	IVTT — linehaul	L/s_{bl}	$v_{ib}L/s_{bl}$
$D \to F$	IVTT — CBD	$(\frac{1}{2}+\frac{1}{4})/s_{bc}$	$v_{ib}(\frac{1}{2}+\frac{1}{4})/s_{bc}$

6.3 Rail transit

In this case we study rial transit with a dedicated feeder bus-access service, assuming that the commuter walks to the nearest bus stop.

Component	**Description**	**Time**	**Value**
$A \to B$	Feeder access	$\pi r/2R_f s_w$	$v_w \pi r/2R_f s_w$
Wait at B	Feeder wait	$\Psi_f/2$	$v_{ww}\Psi_f/2$
$B \to C$	IVTT — feeder	$r/2s_{br}$	$v_{ib}r/2s_{br}$
Transfer time at C	Transfer	t_{tf}	$v_{tf}t_{tf}$
Wait at C	Rail wait	$\Psi_t/2$	$v_{ww}\Psi_t/2$
$C \to F$	IVTT — train	$(\frac{1}{2} + L + \frac{1}{4})/s_{tl}$	$v_{it}(\frac{1}{2} + L + \frac{1}{4})/s_{tl}$

7 User costs

We can now collect terms for the displays of the previous section and write down expressions for the user costs (value of time contributions) by the average user in this corridor, if she uses each of the three available modes. We collect terms in the order: wait costs, access costs (at both ends of the trip, including transfer costs), in-vehicle time costs.

$$uc_a = v_w \frac{1}{4s_w} v_{ia} \left(\frac{r}{2s_{ar}} + \frac{L}{s_{al}} + \frac{1}{2s_{ac}} \right) \qquad \text{(auto)}$$

$$uc_b = v_{ww}\frac{\Psi_b}{2} + v_w \frac{\pi r}{2R_b s_w} + v_{ib}\left(\frac{r}{2s_{br}} + \frac{L}{s_{bl}} + (\frac{1}{2} + \frac{1}{4})\frac{1}{s_{bc}} \right) \qquad \text{(bus)}$$

$$uc_t = v_{ww}\left(\frac{\Psi_f}{2} + \frac{\Psi_t}{2} \right) + v_w \frac{\pi r}{2R_f s_w} + v_{tf}t_{tf} + v_{ib}\frac{r}{2s_{br}} + \frac{v_{it}}{s_{tl}}\left(\frac{1}{2} + L + \frac{1}{4} \right) \qquad \text{(rail)}$$

where the rail costs are for a rail-with-dedicated-bus-collector system.

8 Agency costs

We now consider the question of the costs incurred by the supplier of the transport services. There are two aspects to these. The first is operating costs which we assume that these are of the form [cost per hour] × [hours of service] + [cost per mile] × [miles]. Note that for autos, this is already included in user costs; and that we will want to include all externality costs in these expressions. The second is capital costs, including the costs of guideways/roads. Write ρ_i for the capital costs per hour (these will be "annualized" on a per-hour basis, rather than per-year) on mode i; note that these will depend on the structure of the corridor, in particular its length. If we write c_{Mi} and c_{Hi} for the costs per mile and per hour on mode i, then we have the following agency costs for a 1-way trip on each mode:

$$
\begin{aligned}
oc_a &= \rho_a \quad \text{(auto)} \\
oc_b &= c_{Mb}\left(r + L + \frac{1}{2}\right) + c_{Hb}\left(\frac{r}{s_{ar}} + \frac{L}{s_{al}} + \frac{1}{2s_{ac}}\right) + \rho_b \quad \text{(bus)} \\
oc_t &= c_{Mf} r + c_{Mt}\left(L + \frac{1}{2}\right) + c_{Hf}(\frac{1}{s_{br}}) + c_{Mt}\left(L + \frac{1}{2}\right) + \rho_t \quad \text{(rail)}
\end{aligned}
$$

where (1) the capital cost ρ_t for the rail mode includes the capital cost of its included feeder system; (2) we allow the feeder system to incur different operating costs than the standard bus service and (3) for the bus transit modes, note that the bus travels the entire radius in the residential area, even though users only ride (on average) for half that distance.

For the two transit modes, we can now compute the system costs per hour of service provided. The key is that on each route we have a headway of Ψ measured (say) in hours (recall that the headway is the time interval between vehicles). The inverse of this is the transit frequency on each route, measuring the number of vehicles that traverse the route per hour. Since we have R routes, and they all have the same headway (by assumption), the total number of trips is R/Ψ. Thus

$$
\begin{aligned}
ac_a &= \rho_a \quad \text{(auto)} \\
ac_b &= \frac{R_b}{\Psi_b}\left(c_{Mb}\left(r + L + \frac{1}{2}\right) + c_{Hb}\left(\frac{r}{s_{ar}} + \frac{L}{s_{al}} + \frac{1}{2s_{ac}}\right)\right) + \rho_b \quad \text{(bus)} \\
ac_t &= \frac{R_f c_{Mf} r}{\Psi_f} + \frac{c_{Mt}}{\Psi_t}\left(L + \frac{1}{2}\right) + \frac{R_f c_{Hf}}{\Psi_f}(\frac{1}{s_{br}}) + \frac{c_{Mt}}{\Psi_t}\left(L + \frac{1}{2}\right) + \rho_t \quad \text{(rail)}
\end{aligned}
$$

Note that the literature contains two equivalent formulations of this setup. We have measured bus headway on each route. Alternatively, we can measure the headway as it would appear to a bystander along the linehaul portion of the route. If we do it this way, then the system frequency (total number of vehicles per hour) just the inverse of that headway. However, at the user end, the effective headway on each route is R times the measured headway along the linehaul portion of the trip (if we see buses going by every minute from a point alongside the freeway, and if we know that there are 10 routes, then on each route we would see a headway of 10 minutes).

9 System costs

We can now put everything together. Suppose we are interested in the full costs of moving Q passengers per hour using each of the three modes. Total user costs will then be Q times the costs to a single user, and we have the following expressions for the full costs per hour:

$$
\begin{aligned}
tc_a &= Q\, uc_a + ac_a \quad \text{(auto)} \\
tc_b &= Q\, uc_b + ac_b \quad \text{(bus)} \\
tc_t &= Q\, uc_t + ac_r \quad \text{(rail)}
\end{aligned}
$$