PROFESSOR: OK, so you might recall we had a snow day, and the snow day bumped us. We interrupted our introduction theme and dove right into data collection. Then we did short-range planning. So Neema was lecturing that over two lectures.

Now we're back to the third and last introductory material. And then we'll go back and do more data and modeling if that makes sense. Sorry for that interruption.

So it's a little more general than the other classes that we've seen. And today's topic is model capacities and costs. So we'll cover a simple capacity analysis that you might do, you know, back of the envelope calculation. If somebody is asking you about something, and it's a completely new service, and you just want to have an idea, I will give an example of that.

Then we'll look at worldwide status of urban rail systems, both heavy rail and light rail, some bus ways. And we'll look at capital and operating costs at a high level, focusing more on the US using the National Transit Database.

All right, so first slide here is an update of the statistics I gave you earlier. So you have these statistics from the previous introductory lecture, but these are updated for 2013. So I'm not going to cover this in detail. But if you want to compare with the previous table, you can do so. And here you have more updated numbers. These come from the APTA Fact Book, and they take the numbers from the National Transit Database.

And let's start with that simple capacity analysis. So this is a theoretical exercise, but it gives you some idea of how one might approach-- if you have nothing to go on, how one might approach estimating what capacity you need for some service. So the problem is, given a pie-shaped sector into the central business district served by a single transit line, what will be the peak passenger flow entering the central business district.

And that might give you an idea of what mode you need. Right? Can you run a bus system? Do you need a light rail, a BRT, a heavy rail? So it gives you some idea.

And you might have some statistics about the city where you're being asked about, the question. And so you can make some assumptions. You can draw this on the back of a napkin and, you know, do some calculus with it if you want to. And that's what we're going to do.

So I'm going to draw on the board a little bit. What do we have here? Yeah, I'll draw the same shape here for reference.

So we have a cone-shaped sector or a pie-shaped sector. And there's some angle of that corridor, which is the catchment area over which people might walk to the service. The service, by the way, is along some line, and it reaches the city center, which we're calling the CBD.

And at that center, there is some density, some population density, which we call P sub c, the population density at the center. And at any point along this pie or pie-shaped sector, this, the length of this arc, is r theta, where theta is the angle, and r is the radius from the CBD up to that point.

So r is a variable, and it starts at 0, and it extends all the way up to the length of the corridor, which is L. L is the maximum value r can take. Does that make sense? Everybody following?

OK, and then we take little slices of these arcs. And they have a very, very thin, infinitesimally small width, dr. And we can-- that sort of sets the stage for what we want to do here. Let's assume something. Let's start assuming the population density, which starts at a very high level in the center of the business district, starts dropping as you move out.

That makes sense. Right? In most cities, that's what happens. We're going to assume that it drops linearly and that it reaches some value lower than Pc at some distance L from the CBD.

And if we look at the distance from the CBD here, which we call r, and we start at 0, 0 is at the CBD. Right? We start with a population density of Pc. And we're going to assume it drops linearly to some amount.

And at some point, we'll reach L. And that's where we stop the corridor. So this part doesn't really matter because the corridor doesn't serve the part. And the rate at which that population density declines, we will call delta P. OK, so total population density is decreasing as we move outwards from the center.

All right, so let's start with what is the population in the corridor. Right? Because we need to know how many people are in that corridor. And then from that, we can calculate, based on some assumptions, how many people might access that line. So we'll start with calculating the population in that whole pie-shaped sector.

All right, so call it population. So we'll take an integral from r equals 0 to r equals L, which is the length of the corridor. And we take r theta, which is the length of this arc, which it starts very small and gets longer and longer until we get to this part, which is L theta alone. Right? So this is the arc length. And we multiply by the arc width, which is dr.

And we multiply by the population density. And the population density is a function of how far we are from the center. So that's going to be P of r. And we can call this graph P of r.

The y value here is P of r. It starts at Pc, drops to 0. Or before reaching-- well, yeah, it doesn't get to 0 at the point of reaching L. Right? So it remains positive throughout the length of the corridor.

All right, and now we can just, you know, do some math and calculate this. So I'll just run through it. So we have r theta dr. Let's substitute this function, which is the population density. We assume that it had this shape.

So let's plug that in here. It's a linear function. So it starts at the center with a high number, and it decreases as a function of r at a rate of dP and times r. Right? So when r equals 0, there's no decrease. As you move this way, you multiply r times dP, and you get the difference between Pc and the point where you are.

All right, here I'm just going to collect terms to make things look a little nicer. All right, so again, we're just distributing this times that and that times that. So we have now two integrals.

We can take some constants out. So theta is a constant, and Pc is a constant. So we can take those out of the integral. And we continue integrating from 0 to L. But now we have a simple thing, r dr, which we know how to integrate.

And then here, dr is-- sorry, dP is given. So we have an assumption about what that rate is right so dP is taken out as well as a constant. And we, again, integrate from 0 through L. And sorry, and theta is also constant. Right? So we can take that out. And we have r squared dr.

So now it looks a lot simpler, and we can do the simple integral. Right? Integral of r dr is r squared over 2. Integral of r squared is r cubed over 3. So we can substitute that in.

So we have Pc theta over 2 times r squared-- and r squared goes from 0 to L-- minus dP theta over 3. And we have r cubed going from 0 to L.

And now we just simplify things, and we compute the going from 0 to L on both sides. So we are left with Pc theta over 2 times L squared. When these ranges are 0, this term is 0, and that term is 0.

So all that matters is plugging in-- substituting L for r. Right? And the terms of minus 0 are 0. So we don't need to write them.

dP theta over 3 L cubed-- and just collecting terms, the ones that look similar-- Pc/2 minus dP L/3. OK, so this is the population in the corridor. And it's a function of the properties of the corridor. Right?

So if the corridor is longer, then we have a higher population. If the angle of the corridor gets wider [INAUDIBLE] population in the corridor. That also makes sense.

And then it also depends on the population of the city center-- the higher it is, the bigger the population in the center. And it depends on the rate at which the population decreases from the center-- the smaller the rate of decrease, the larger the population. Right? Does that make sense?

OK, and now, in terms of peak passenger flow, we can look at units, but we'll have to add some assumptions. So actually, I think, at this point, I can probably stop the math on the board and just go straight to it. So this is the modeling part. And now we're just going to make some assumptions about-- given that the population in the corridor and some assumptions about what L and theta and Pc and dP are and some assumptions about the share of those people that would take transit, we'll look at what the peak passenger flow is. So let's go straight to it.

Here we have the variables that I defined on the board and some additional ones. We have t, c, m, and p. Right? So t is the number of one-way trips per person per day. We're going to have to assume this. c is the share of trips that are inbound to the CBD, as opposed to going outbound. Right? So it's what percentage go inbound.

m is the transit market share for CBD-bound trips. So some people will take cars or other modes. And we want to have some assumption about what percent of people that are going into the CBD will take transit, as opposed to other modes. So that's m.

And p is the share of CBD-bound transit trips in the peak hour. So we want the peak hour flow. And maybe we don't want the whole day. We just want peak hour flow. So there's going to be some percentage of that.

So here you have the same equations that I have on the board. And the peak passenger flow is what we have there, which is the population in the corridor multiplied by our four assumptions, our four factors that are going to convert the population in the whole corridor to what percent of people are going to go into the CBD taking transit. Again, this is a very simple, theoretical exercise, but it could be useful at some point.

And we'll just plug in for two examples. We have two scenarios here-- one where the population density in the CBD is 10,000 and another one where it's 20,000. For reference, in New York City, the population density is about 28,000. So these are not as high as those very dense cities.

AUDIENCE: But like what is 10,000 [INAUDIBLE]?

PROFESSOR: Depends how-- again, it's the same thing. Like it depends how far you go and what you define as the center. But here are some numbers. This could be some city. Right? These are typical of some cities.

So here we have some decreases and the rate of decrease in the population from the center going out. We're assuming a 40-degree angle for the shape of this. If you have a city, you know, you have several lines going in radially. This transit corridor serves about a 40-degree angle. So--

AUDIENCE: Is that-- that seems like a lot.

PROFESSOR: It is a lot.

AUDIENCE: Like maybe a little too much.

PROFESSOR: Well, it depends how many--

AUDIENCE: [INAUDIBLE] 40 degrees like in the inner part, but, you know, 40 degrees you go [INAUDIBLE] miles out. Now you're already making a [INAUDIBLE] arch.

PROFESSOR: At the end, it sounds like a lot, but, at the beginning, not so much. If you think of a city, you know, and you have-- these are 90 degree angles. Right, and you add two more lines. That's 45. So we're how many lines would you have in a city? And it sort-- right? So it's not that unrealistic to think of some line with a 40-degree angle coming into the CBD from outside.

And we're assuming a 10-mile length and factors-- so here we have 2.5, 0.2, 0.5, and 0.25. So that's the assumptions for the different constants to convert the whole population into the number of people going inbound in the morning rush taking transit. All right, so if we plug that in, we get a required capacity of 10,000 in the first scenario and 30,000 in the other scenario.

And then from that, one could say, well, can I have a bus system serving 10,000 people per hour? Or can I have a bus system or a rail system serving 30,000 people per hour. That's accommodating a flow, which this is, again, a back-of-the-napkin calculation, but it gives you an idea of, based on the characteristics of some city, what we would need.

So let's look at some theoretical capacities now. So in this slide, we are looking at kind of high-end, upper bounds almost on these modes.

So for rail, let's assume a very long train, which is 10 cars long, and it's packed with 200 people per car. And it runs at a high frequency, every two minutes. That gives you 60,000 passengers per hour. So that's about as much as a metro system can provide in terms of capacity or a line, metro line, a single metro line.

If we look at bus, so a full bus, 70 passengers, that's quite packed. You could run, if you have multiple bays, you could run 30-second headways. So if you see, BRT corridors have capacity to do that.

Obviously, if they are queuing up to serve a single stop, that could not happen. But if you have multiple bays, that can happen. So based on that assumption, you can get 8,400. All right, so that's pushing the limits of bus.

BRT-- BRT vehicles are longer. So you might fit 200 people in one of these double-articulated vehicles. You might have even 20-second headways with good facilities. That gives you 36,000 passengers per hour, again, pushing the limits here.

Light rail, I have to say that I'm assuming a two-car train here, but we could have three-car train. So maybe I'm not pushing the limits as much on light rail here. But based on a two-car train assumption and 150 passengers per car, which is quite a bit for a light rail car, and assuming one-minute headway, that's 18,000 passengers per hour. Right?

So you can compare these. And again, these are all kind of upper bounds. Maybe light rail can be pushed a little higher. But it gives you an idea of what the theoretical capacities are.

So now we have this back-of-the-envelope calculation-- 10,000, 30,000. And what would we need for 10,000? Could we serve that 10,000 demand with a bus? Probably not. Do we need rail, BRT, or light rail? Probably so. So it gives you an idea.

And if it's the 30,000 example, well, it looks like we're going to need rail. Right? Because BRT is kind of-- you're getting to the high end of that. So we're probably going to need rail for that.

OK, and now let's look at what happens here in Boston. So it's much lower here, nowhere near the theoretical capacities, right, that we're talking about. These are peak-hour volumes for the different lines.

So if we look at the Red Line, which is the most crowded line, in the Cambridge section, which is the most crowded, especially between Central Square and MIT-- actually, that's the highest point on the system-- we have almost 10,000 people per hour, passengers per hour.

AUDIENCE: We saw in a different course-- one of the people from the T who came who was a graduate of the MST program showed slightly higher numbers than that.

PROFESSOR: Yeah, so these numbers are a little dated. And it depends on how you define the peak hour. And you know, I could show you the peak 15 minutes, and that would be higher than this, for example.

So if you look at the peak-- yeah, like the peak of the peak, it's even higher than this. But it still is the case that these are not approaching the theoretical capacities. And that's because we don't have, you know, two-minute headways and 10-car trains or yeah.

So right, so the Orange Line, we have two sections here, the north and the southwest, similar numbers. Blue Line is slightly lower. On the Green Line, the branches do about, you know, 1,800, less than 2,000 each. So we're looking at a much lower number than the light rail theoretical capacity.

And in the central subway where all these branches merge, we get a much higher demand, but it's still lower. Again, these vehicles are not running every minute. And in some cases, they are, but not consistently. And we don't fill all the vehicles, you know, to crush load for a whole hour. Right? So we're not getting that capacity. We're not delivering that capacity.

So it gives you an idea where we are. If you've used the system here in Boston, you might relate taking the train at peak hour to what these numbers look like and think about what it would take to increase capacity in terms of more cars or a higher demand spread over a longer peak and things like that.

OK, now let's look at worldwide urban rail systems. This is metro, and I have grouped it by continent. And it starts sort of before the 1900s.

And you can see the earlier systems started in Europe-- London, Budapest. Right? And then North America followed closely after that. Boston takes the prize for the first subway. That's the Green Line. And even though we call it light rail here, we're calling it metro in the slide.

So we have a few starts in North America, and it sort of falls flat in 1920s and 1930s. And then it takes off again-- 1960s all the up. It keeps increasing.

Asia was a little slower to start, but it's going up really fast. China is building a lot of metro. Africa, I think it has two systems right now. And there are no systems that I am aware of in Australia, but they are building one that should start before the end of this decade in Sydney. So they're going forward with that.

So this is, you know-- you can see that we're building metro and that it goes together with what we said on the first class. Population is increasing. And especially urban population is increasing. People are moving away from rural areas into cities. The required capacities to have agglomeration benefits and avoid traffic and air pollution problems is requiring higher density, higher flow systems like metro. Questions?

AUDIENCE: So you've got Australia has some very dense cities of course. How do they move people in? Like do they have BRT systems?

PROFESSOR: Yeah, so they have BRT. They have light rail.

AUDIENCE: Melbourne has the longest light rail network in the world.

PROFESSOR: Yeah, and they have pretty good BRT.

AUDIENCE: The bulk of Melbourne is electric commuter trains that operate at sort of subway-level headways. So it wouldn't be included in your--

PROFESSOR: So yeah, we're not counting them here. And so good point, it's hard to-- there are many ways of accounting for systems here. Sometimes, you know--

AUDIENCE: Commuter rail and heavy rail.

PROFESSOR: Yeah, that might be mixed. Or do they count those as two or as one if there are different systems in one city? I've tried here to count each city as one system, even if there are multiple systems.

So for example, I'm not counting the Tube in London and Docklands Light Railway as two systems. I'm counting them as one. But some people would count them as two. So there is some arbitrary choice to be made here in accounting, but it gives you an idea of what the trends are and how we are moving and how it started and where we are right now.

Here's light rail, light rail and streetcar. So if we only looked at light rail, it wouldn't look like this. This includes streetcars, and that's why we start so early before the 1900s in Europe and Asia as well. And then North America really didn't follow until much more recently.

AUDIENCE: Well, North America, it's like [INAUDIBLE]. If you include North America, every city had streetcars.

PROFESSOR: Yeah, but they're not operating right now.

[INTERPOSING VOICES]

PROFESSOR: Yeah, but they're not currently operating.

AUDIENCE: You would see [INAUDIBLE].

PROFESSOR: Yeah, so that's right. So that's another good point. So if we included things that were operating and no longer dropped, then this graph would go up and then down. And these are based on statistics of currently-operating systems that started at some point in the past. Right? So that's a good point. Thank you for bringing that up.

And we see here Africa, Oceania, so Australia-- and let's see. Yeah, Africa, South America, and Australia don't have many systems. Right? So mainly, we have [INAUDIBLE] in Asia, and increasingly so in North America, but not at the same level as in Asia. Obviously, that has to do with the size of the cities and the number of large cities as well.

So OK, capital costs, so these are based, once more, on the NTD numbers, the National Transit Database. These are 2013 numbers that were published in the 2015 APTA Fact Book. And you can download that on Stellar if you want to look at these in detail. So $18.2 billion was spent in capital costs, and we're going to look at how that cost was distributed.

So if we look at by type, about a quarter of that was spent on purchasing vehicles or rehauling old vehicles for their midlife repair. And about 60% was spent on infrastructure and facilities. All right, so that could include new rail lines or extensions, repairs of those, bus stops, maintenance facilities, right, offices, things like that.

And then about 15%, 16% was spent on other things. Those other things could be AFC systems, other things that are not vehicles or facilities. Right?

So OK, by mode, about a quarter was spent on bus projects, about 35% on heavy rail projects, and then less, a little less, on commuter rail and light rail, and then 5% in other modes. And that's mostly paratransit or demand responsive, as they [INAUDIBLE] APTA Fact Book. So it gives you an idea of how the US, on any given year, distributes the capital expenditures.

You might think that, from year to year, these costs vary a lot because capital investments are very lumpy. Right? You don't have them, and, all of a sudden, you invest a lot of money into a system. But because there are so many cities, they don't actually vary that much.

And the other reason that doesn't happen is because a lot of the expenditures are gradual. So it takes several years to build new lines. So they are distributed over several years, instead of all at once.

And here we have the breakdown by mode and type at the same time. So about-- the key takeaway here is so $4.5 billion was spent on bus projects. And about half of that was on vehicles and about half was on facilities, the repair facilities, bus stops, things of that nature.

When we look at rail, the percent spent on vehicles is much lower. It's about 10% to 20%, 7% to 20% in this case, depending on the specific rail mode. And closer to 90% is spent on infrastructure and facilities. That makes sense. Right? You have to lay-- you have to sort of put rail. You have to build stations. The maintenance yards are more expensive.

So these are bigger projects. To the extent that the right of way is a subway, then you have to dig. And so it's very expensive. And here you have the total expenditure, capital cost by mode.

And so 4.5 on bus, 6.2 on heavy rail, 3 on commuter rail, 3.5 on light rail.

OK, and now focusing on infrastructure costs, so what drives the infrastructure costs? First, the type of construction, right, so if we look at heavy rail, you could build at grade, so leveled on the street or on sort of new lands that you don't have to acquire from anyone. That's the least expensive. Then you move to elevated. If you have to go over streets, and you have an elevated section, that's the second most expensive.

And then subway tends to be the most expensive. And there are two ways of doing that. There's cut and cover. So that's a shallow tunnel. You dig a hole. You put the rail lines, and then you build a roof on top of it, and cars drive over it. That's shallow tunnel.

And then there's deep tunnel, which is the most expensive. That tends to be with a tunnel boring machine. So you get these huge machines that drill the hole. They're very fun to learn about and look it. I encourage you to YouTube them.

And they are usually built for the project. And when they finish digging, they are sort of taken off course. And they sort of remain interred at the level. So they're kind of used once, and there you go. So London has used a lot of these for their very deep Tube. And yeah, you should look at these on YouTube.

AUDIENCE: In New York, it's kind of common. Right?

PROFESSOR: Yeah, yeah.

AUDIENCE: It basically goes along the avenues.

PROFESSOR: Yeah, so in London, we have both. Right? So the earlier lines like the Central Line and the--

AUDIENCE: Yeah, the Circle and District.

PROFESSOR: The Circle and District Lines are definitely cut and cover. And then the Silver Line is very deep. Right? And so that's a tunnel boring machine.

AUDIENCE: Can you give a sense of the difference between let's say at grade, elevated, and shallow and deep?

PROFESSOR: Maybe I should have shown some pictures. But at grade is just at street level.

AUDIENCE: No, I know, but like the difference in cost.

PROFESSOR: Oh.

AUDIENCE: Like cost per mile.

PROFESSOR: Oh, I'll give some examples in the next few slides. Yeah, that's a good segue. So the other key factors are land acquisition and clearance. So if you're building a new line, and you have to use eminent domain and sort of buy property from people who own them, who own that property, to build your new line, that costs some money.

Also, the number, size, complexity, and length of the stations-- so station design is a key component here and the complexity of the system. Is this an independent line? Or are there many points of transfer? And how do you coordinate that? During construction, do you have to keep operating some parts of the line? How do you manage that?

So if you look at, for example, the repair of the bridge, the Longfellow Bridge here in Boston, we wanted to do that with rail, for the most part, running. So that has increased the costs of that project. You couldn't just take the bridge down and rebuild it. And we wouldn't have the Red Line for a long time.

OK, so here are some typical costs. Here are some, four examples. Right? And they vary a lot, but it gives you some idea of the magnitude of these costs.

So Tren Urbano was one of the most recent systems. It was built in 2002 in San Juan, Puerto Rico. And it 50% at grade, about 40% elevated, and 10% subway, just a small section that was subway.

It cost about $2 billion to build. And if you divide that by the length of the corridor, it comes out to $118 million per kilometer. Right? So it gives you an idea of what it takes.

The MBTA Red Line in 1984, it was extended to Alewife from Harvard. And that was 5 kilometer extension, four stations. It was all subway. So it cost $0.6 billion of $600 million. And that comes up to $120 million per kilometer. All these figures are in the dollar numbers of the year that they were built. They're not adjusted for inflation.

Then we have the Los Angeles MTA. That was a new system started in the late 1980s. It was all subway, 7 kilometers. $1.2 billion comes out to $180 million per kilometer, so same range, right, or similar. I mean, obviously, from 120 to 180, it's 60 million. That's a lot of money, but same ballpark, same order of magnitude.

WMATA was cheaper on a unit cost basis. It was built over several decades, multiple phases, 100 kilometers, so lots of stations, lots of distance covered. It's a mix of subway, elevated, and at grade. And it cost $6.4 billion, and that comes out to $60 million per kilometer. So yeah. Question?

AUDIENCE: Can you say what is WMATA again.

PROFESSOR: WMATA is the Washington metro, Washington, DC.

AUDIENCE: Washington, DC.

PROFESSOR: Washington, DC, yeah. Yeah, [INAUDIBLE].

AUDIENCE: [INAUDIBLE] So since this--

PROFESSOR: In one year.

AUDIENCE: Yeah. So since this remains the same across years--

PROFESSOR: More or less. It varies, but it doesn't vary drastically is what I wanted to say.

AUDIENCE: So would that mean that in fact we're declining the amount we spend on transportation because this is not inflation adjusted?

PROFESSOR: This is not inflation adjusted. That's right.

AUDIENCE: So it's the [INAUDIBLE] are declining, right? [INAUDIBLE]

PROFESSOR: For heavy rail, yes. Yeah, maybe, yeah. We're building a lot of light rail and stuff. But there is still some expansion or repair or--

AUDIENCE: Does this mean the Second Avenue subway extension isn't in the same order of magnitude as any other--

PROFESSOR: I'm not familiar with the unit costs for that.

AUDIENCE: I read it was like $2 billion per kilometer.

PROFESSOR: Yeah, I mean it depends on many things. So--

AUDIENCE: Well, so recent lines, I mean Seattle was about $1 billion per. And San Francisco Central Subway was about $1 billion per. So modern subways are-- the stupid GLX, the Tremont extension was $500 million because the T can't procure a project out of their butts, but it's still still four times cheaper than Second Avenue subway.

Well, but it's also being built at grade, and it gets the right of way.

PROFESSOR: So many factors there. Let's look at light rail now. So LA MTA, 30 kilometers at grade, so a long distance, but all at grade-- $690 million, this includes stations and vehicles. That comes to $23 million per kilometer. So you can see that these costs are a lot lower. A lot of that has to do with it being at grade and also not being as complex of a system. Yeah, you have a question.

AUDIENCE: Yeah, are these costs for just the parts that were built in the late 1980s and not over time. Like the most recent one is not included in that.

PROFESSOR: Not including the most recent ones, that's correct, yeah. So Buffalo, 10 kilometers, but subway, cost almost the same, even though it was a third of the length. It comes out to $53 million per kilometer. Santa Clara, 30 kilometers at grade, so very similar to LA MTA, about $500 million, $16 million per kilometer. So you can see that, even in similar systems, there are other details that might affect cost significantly.

And then Portland, mid 1980s, 24 kilometers at grade, $214 million, about $9 million per kilometer-- so that was the cheapest of these examples on a unit cost basis.

AUDIENCE: Remind us what a light rail subway is again.

PROFESSOR: So yeah, these are terms that are arbitrary, but our stereotypical definition that we are using here is a lot of it tends to be at grade, not always. It could be subway. It tends to have electricity from pickup lines on the top. You might have some sections where people board sort of straight from the streets. All right, so there is not a special platform where-- like a subway station where people tap into a gate and move in.

AUDIENCE: This is not that.

PROFESSOR: Right, yeah.

AUDIENCE: Light rail subway.

PROFESSOR: Yeah, yeah, yeah. So--

AUDIENCE: People are walking into the--

PROFESSOR: Yeah, so when we look at heavy rail, we're thinking about things like the Red Line and the Blue Line and the Orange Line here. When we look at light rail, we're thinking more like streetcars and the Green Line here in Boston. Right? So the Green Line is more like light rail. Even though it has the subway portion, it's operating like a light rail in some part, subway part.

Yeah, but if we look at other countries, some systems are called light rail. Docklands Light Rail in London, false-- if we describe it, we would classify it as heavy rail with these descriptions. And in Asia, we see a lot of systems called light rail, which are, by these descriptions, heavy rail. So the terms are used with caution.

OK, busways, so the South Boston Transitway was 2 kilometers. That was the Silver Line tunnel, right, cost $606 million-- that does include the purchase of vehicles-- and so $303, of course, million per kilometer. TransMilenio was 36 kilometers at grade in the early 2000s, $200 million, $5 million per kilometer. Seattle, 2 kilometer of bus tunnel, $319-- $160.

So the takeaway here is, if you're making a tunnel, you can see that the first and third examples are tunnels. Right? And they cost a lot more in the hundreds of millions. And the three that are at grade, second, fourth, and fifth examples, two of them in the 36, 35 kilometer, and this one a little shorter, are in the two-digit, single-digit million dollars per kilometer.

AUDIENCE: TransMilenio, you're talking about like the first, initial--

PROFESSOR: Because they've kept growing is what you're saying, right? I don't know-- I don't remember what range of years this includes exactly. But yeah, I'm saying, you know, whatever they were sort of starting to operate in 2001. Yeah.

And you can see here 36 kilometers at grade. So we could then go look and see what is that 36 kilometers at grade that they built around 2001 to see. If they've expanded more recently, that's probably not included here. Yeah. Any other questions?

So these are examples to give you an idea of what it costs or what it has cost. OK, generic costs for rail, so it costs from about $2 to $2.5 million per car for a heavy rail train. So if you calculate what capacity you need, and you think you need a fleet of 200 vehicles, you can take these numbers and multiply by $2.5 million. You have some idea of how much it costs to purchase your fleet.

Some recent-- a recent CNR, it was a large procurement. And that helps bring the unit cost down. So 284 cars replaced Orange and Red Line vehicles. Siemens in 2010, it was about $2.3 million per car. That was for 94 Blue Line cars.

Then we have Hyundai Rotem, $2.3 million per car-- these are 75 commuter rail cars, rather than heavy rail cars. Breda, $2 million per car-- these are the Green Line cars, 95 of them. And the last example are locomotives for commuter rail, $5.7 million per locomotive. So they cost more, but these are not all passenger cars. These are the locomotives for the commuter rail system.

And for bus, so a standard bus, a CNG bus, the Compressed Natural Gas, these are, again, recent MBTA orders-- the generic cost, $300,000, $350,000 about per bus. There was an order to NABI, and it was for 300 vehicles in 2004. And that was $320,000 per bus.

Trolley, 40-foot trolley is about $1 million per trolley. These are the sort of electric Silver Line vehicles I think. I'm pretty sure. The articulated, 60-foot CNG buses, 44 vehicles in 2003, and the articulated, dual-mode, 60-foot buses-- this is Silver Line, the one that runs in the tunnel and goes out to the airport-- $1.6 million, 32 vehicles, 2004. Yeah.

AUDIENCE: Maybe this is already happening, but is there any move for different transport organizations to consolidate their designs and like be able to reuse vehicle design and bus design? Like why are there separate things for all cities?

PROFESSOR: That's a good question, but a lot of it is cultural. There are-- so for example, Green Line here has sort of specific needs with respect to like turning radius, and they have a lot of steep grades in some sections. They're also used to a certain type of vehicle. So they're more comfortable procuring vehicles that are similar to what they've had in the past. So there's some resistance to trying something very new all of a sudden.

But there are some vehicles that are very common, especially in newer systems. And they tend to be a little cheaper. So yeah, if you can get big orders, or if you're a small system, and you can partner with someone else when they are procuring to procure additional vehicles-- instead of you doing 10 yourself, you add yourself to an order of 100. You get a lower price. So yeah?

AUDIENCE: But then there's certainly two examples of that in streetcars, the most recent one, which was when the Boston and San Francisco bought a similar design for streetcars in the '70s, and both got a crappy product. But 50 years before when the PCC cars, the ones that still run down in Mattapan, was a sort of standardized streetcar design over most of the country, and that worked really well. So it has been done, but--

PROFESSOR: Yeah, and still is done, I think. Yeah, yeah.

AUDIENCE: But each system, I think, has so many [INAUDIBLE] things.

But when it comes to buses, then you do see the same types of buses like in many systems. In Europe, you only have like two or three manufacturers that make them all.

In the US, as well.

PROFESSOR: And big procurements, not so much for bus, but for rail, a lot of big procurements have rules requiring local manufacturing. So yeah, you get a Chinese company to do the latest-- where was that example-- CNR, right, but I'm pretty sure that a lot of the manufacture is happening in Massachusetts or close by.

So OK, typical capital costs per passenger mile, so looking at a range of examples, it will cost [INAUDIBLE] going anywhere from $0.05 to $0.10. So if you have-- again, if you're doing the napkin calculation on a new system or new line, you might think how many passenger miles do I have. You could multiply by this to figure out how much you could expect to spend on vehicles.

And for infrastructure, that could range anywhere from $0.01 to $1 because there are so many ways of doing this. Right? It could be a subway. It could be at grade. It could be a bus. Or it could be rail. So it's very variable, and you need to get into the specifics.

OK, now let's look at operating costs. We've been talking about capital costs. Let's look at operating costs. So in the US in 2013, we spent $42.2 billion across the industry. And if we divide that by type, about 44% was spent in vehicle operations, and the rest of it was more or less evenly distributed between vehicle maintenance, other kinds of maintenance like facility maintenance, administration, and purchased transportation.

Purchased transportation is when a public agency outsources the operation of some mode. Most of this 14% is paratransit, so on-demand transportation for the handicapped and other groups. Some of it is commuter rail. So for example, the MBTA operates commuter rail through a third party.

All right, OK, by mode, about half is spent on buses-- makes sense because there are more bus systems and, even in cities that have rail, but the bus systems are quite large, and they cover a wide area-- about 20% on heavy rail, 13% commuter rail, and much less on light rail. Paratransit is about 12%, 3% for other modes. Other modes is things like ferries and other modes not included in the traditional bus, heavy rail, commuter rail, light rail.

So OK, and let's look at vehicles-- sorry, employees per running vehicle. So by mode, how many employees would you have to have to operate, to run a system? So paratransit, about 1.6 per vehicle-- obviously, you have one person driving a paratransit vehicle. That person has an eight-hour shift, and you run that vehicle for a longer time. So you need more people than vehicles.

Bus tends to be higher because bus systems tend to start much earlier and end service much later. And you also have maintenance yards and refueling facilities. Right? So you have bus stops to clean. So it's a more intense operation.

Commuter rail, 4.7-- you have the people driving the locomotives. You have the attendants looking at tickets. You have rail to maintain and stations to maintain. So that's commuter rail.

Heavy rail is 5.5. Again, it starts early, runs late. You have a lot of stations to maintain, more so than commuter rail, so 5.5.

Light rail is 6.8. Part of the recent light rail is high is because many systems have one driver per car. Or some systems, at least, have one driver per car. So here in the Green Line, we have that. Right?

So if you have a two-car train, you have two drivers. And again, it starts service early, ends service late. So you [INAUDIBLE]. You need multiple shifts to run the whole day.

And you have maintenance of stations. Light rail stations [INAUDIBLE] be shorter than heavy rail. So they have more stations to take care of. And then there's maintenance, vehicle maintenance and facility maintenance. [INAUDIBLE] is about three employees per vehicle.

OK, so comparing, these numbers below are from a 1970 study on employees per vehicle. And it's a comparison of bus and rail. So what's neat about the comparison at the bottom is that we are distributing the costs of a vehicle not only by mode, but also by what type of expense. Right?

So at the top, we're saying bus is this much. Here we divide it by vehicle operation i.e. driving, vehicle maintenance, management and control, fare collection, way maintenance, and then you have the total number. So it is from an earlier study. But for vehicle maintenance, it's more or less the same on a unit cost basis.

For bus, this is per car, and that's per vehicle. So you have about 2.2 drivers per bus for bus systems, about 1 for rail systems. This is driving, but also other things. Management and control is about the same.

And then the driver takes care of fare collection on bus. But in rail, you have people that have to sort of be station attendants and help people out. You might have an office where people can complain about their needing a rebate because their machine didn't work or something. They lost value on their fare card.

So way maintenance is more expensive, whereas way maintenance on buses on the streets, that's not even included in the cost for running bus systems because that's-- the Public Works Department takes care of that. So overall, it's higher for rail than bus. But you have some-- yeah, so you do have a higher productivity for metro if you measure it in passenger miles per revenue vehicle hour.

Yeah, so if you have any questions, I'll take them, questions on the homework or on this lecture or on the previous lectures. And if you don't have questions, you may leave.

AUDIENCE: Is that [INAUDIBLE]?

PROFESSOR: You were first, yeah, Scott.

AUDIENCE: [INAUDIBLE] on slide 18 looking at capital cost over passenger mile, do you need to pick a time period in order to make that calculation.

PROFESSOR: This is very general. So this is sort of high level, looking at the whole industry and looking at like capital projects. So you know, if you look at how much it costs to build a new line, a new light rail line in some city, and then you see how many people are taking it-- so we have passenger miles. So you divide the total cost by that, and that's what you get. You have a question.

AUDIENCE: Yes, so regarding the homework assignment, we are-- basically, we should do the assignment and maybe comment on, but assume that we don't know-- we won't have like the-- what am I trying to say? It seemed like there was a lot of information that you have already asked if people who are taking the train the one stop that we are.

PROFESSOR: Yes.

AUDIENCE: So we just assume [INAUDIBLE] covered in the data collection and assume that that data exists, but that we don't have it.

PROFESSOR: Yes, yes. So there are people who-- I think what you're referring to is there are people who are going to MIT who get off at Central Square and transfer to the Red Line, right, and go to Kendall.

AUDIENCE: Yeah, especially the Kendall area.

PROFESSOR: Right, now how many of those would continue on the bus rather than switch anyway? I'm not sure. So there is a judgment call there.

But yeah, we're focusing on the people that for sure would stay on the bus. They're not transferring to Kendall. So they're going somewhere else in that area before reaching Kendall possibly, right, or almost surely. And those are the people that would definitely stay on the bus.

AUDIENCE: That we talked to.

PROFESSOR: Yeah, yeah, exactly, which is why we picked that bus stop. But I think it's very likely that, in a future assignment, I will give you data on the people who are transferring to the Central Square Red Line. And therefore, you'll have the whole picture of from your survey and from the ODX data, yeah, AFC data from Red Line.

AUDIENCE: Great.

PROFESSOR: Any other questions? All right, goodbye.