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**DAVID HSU:** My name is David Hsu. I'm a Professor of Urban Studies and Planning at MIT. This is another installment of my class on Urban Energy Systems and Policy. Thank you for joining me.

Today, we're going to give the third lecture on transportation, and I'm going to talk about transportation systems. In the first lecture, we talked about transportation technologies from a personal transport standpoint. We used that to build up our understanding of the technologies involved. In the last class, I talked about policy analysis and how to analyze transportation systems. We talked about it mostly on an equity basis.

Today, I want to talk about it on an efficiency basis and use efficiency to talk about what cities can do, what cities can do to affect a transportation system that is governed at the local level, but also, the regional, state, and federal level, also. So the materials for today are on the syllabus. I'm going to spend most of my time talking about fourth bullet point, which was not a reading I assigned for this class. It's a report by Cambridge Systematics and the Urban Land Institute. It's titled, "Moving Cooler, an Analysis of Transportation Strategies for Reducing Greenhouse Gas Emissions."

I'll tell you a little bit why I didn't assign it as a reading, but at the same time, I'll spend most of the lecture talking about it, so you won't necessarily find this lecture-- or it's not a part of our assigned reading, but I encourage you to listen to the video lecture because there's things I want to pull out of that lecture for class discussion on Thursday. Just to remind you, what can cities do? Why is that an important question?

I'll remind you that we're focusing on cities because of population. Majority of human beings globally and in almost all countries or all regions of the world live in cities. With that population, we have a very high degree of economic activity. And of course, cities are centers of consumption.

While we do have cities that produce energy and materials and goods, in general, in urban areas, we consume things from the outside, like food, like materials, like fuels. And so our cities are our centers of consumption, not production. And so we have to think about the role of cities in reducing consumption to achieve our decarbonization goals.

This raises questions about how we are going to make the necessary changes in cities. We know that cities are composed of the land use and the built environment. I've just made the point to you that cities are connected to outside areas. Basically, all outside areas, we import materials, foods, and fuel into cities. So how do we think about changing cities, or what can cities do in a larger transportation system?

And we also know that while urban life seems very fast-paced, we also know that buildings and the shape of cities are also long-lived, durable, and seemingly slow to change. So the question is, can we make changes at the urban scale fast enough or broadly enough? Who's going to do it and how are we going to make these changes?

And of course, from an efficiency perspective, we have to ask, what should we do first to try to achieve better environmental sustainability or decarbonization? And I just want to emphasize that a lot of the characteristics we are concerned about in cities or why we think cities are harder to change quickly are similar characteristics to infrastructure. To put it simply, infrastructure is really big. It is also a long-lived, durable, and seemingly slow to change.

Infrastructure is really expensive. It's composed a lot of assets and investment. It's often debt financed over long periods of time. It's debt financed over long periods of time because infrastructure is assumed to operate on a fairly continuous basis.

We move large volumes of things. We have continuous operations, and they connect to global systems. In other words, our supply chains that we have seen stressed over the last couple of years.

We know that infrastructure physically has very large footprints and areas and impact. And we know that we have environmental justice concerns. The Bullard article, I think, quite convincingly argues that infrastructure, such as transportation, is often cited-- apologies for that misspelling there-- cited near poor and minority communities. The article examines why, but also, examines why the environmental burdens of these infrastructures are quite often cited near poor and minority communities.

One last thing I want to talk about before we talk about analyzing transportation systems and understanding what cities do is the concept of energy density. We know that energy can be measured in terms of the sheer amount of energy, but more useful for certain kinds of systems, it's good to analyze certain metrics. So in terms of weight, we might think about how much energy certain technologies store, like kilowatt hours per kilogram. Critical applications are planes, cars, and e-bikes, because we know the batteries themselves or the fuel tank is a really large portion of the vehicle weight itself. It's hard to keep planes in the air.

A heavy car or heavy bicycle doesn't perform similarly to a lighter bicycle or a lighter car. We can also measure things in terms of energy required to ship a certain amount of weight, kilowatt hours per ton. That matters for planes, but also, ships, trucks, and trains.

We can measure energy in terms of kilowatt hours per liter of volume in terms of the fuel tank. Planes, cars, trucks, you know that the fuel tank is not a small portion of the vehicle volume. And of course, we can measure how much freight volume we can move for large amounts of commodities in planes, ships, trucks, and trains.

We can measure energy in terms of land area. For example, the kilowatt hours produced per acre, let's say, biomass. We can go-- we're going to need biomass to produce liquid fuels and hydrogen. Or kilowatt hours per acre to generate solar and wind, producing electricity.

And finally, there's the energy density of-- energy density per money, or kilowatt hours per dollar. We obviously need to know that for pretty much everything to deploy different technologies. This brings us to the Moving Cooler strategy report.

It was written in 2009. It was written by this entire group of different agencies and environmental groups, ranging from the American Public Transportation Association, the Intelligent Transportation Society of America, and the Shell Oil Company, to the Environmental Defense Fund, the Federal Highway Administration, Federal Transit Administration, and the US Environment Protection Agency, and a few other groups and agencies. The key point is that this is actually a fairly unusual report.

It was meant to bring together a lot of disparate groups to think about how to reduce greenhouse gas emissions in the transportation system, which is very much tied up to-- tied up with our urban life, which is why the Urban Land institute helped convene this report and workshop. And it's important to note why, I guess, I didn't assign it as reading this year. I've assigned it in previous years.

It's a 2009 report, and, honestly, it gets very technical in places, so I decided not to assign it this year. But I want to highlight some of the findings in this video lecture. It's important to note what the report does have that makes it a really good report.

It does have a consideration of telework or less work days at the office. Now, we know, after two years of Zoom, this is possible, and perhaps, even preferable now. It does include changes in vehicle technology, fuel technology, travel activity, vehicle system operations, and crucially, includes all different modes of transportation, passenger modes, transit modes, freight modes, shipping modes, to aviation modes.

What it doesn't have: It's a 2009 report, but it doesn't actually have shared vehicles. Zipcar was the business model where you could share vehicles in your neighborhood. I think it has since been bought by Hertz. And I'm not sure if Hertz still offers the vehicle-based shared vehicles.

The report written in 2009, which is the same year that Uber starts ride sharing, and Lyft follows three years later. It doesn't include autonomous vehicles. Arguably, autonomous vehicles may be a few more years off now than we think they are. But it also doesn't include the fact that electric vehicle costs have greatly decreased, that we're seeing increases in micromobility, like scooters and electric bikes.

It does include bike sharing, which was started in Amsterdam in 1965. It was deployed at Portland, Oregon in 1995. And dockless bikes started being deployed in 1998.

So this report has good aspects. It also lacks other aspects. It also considers performance outcomes. It does look at greenhouse gas reductions. It looks at the implementation costs, which is important. It looks at the change in vehicle costs required to achieve the performance outcomes, and it looks at equity effects.

It doesn't necessarily look at travel times, one of the reasons why we care about transportation. Like in the pie graph before, we care about how fast these modes are, even if they use different amounts of energy. It does not, I think, look at the positive, which is if we would expand options, reduce congestion, or enable greater accessibility.

It doesn't look at improving safety, which is something we care about in, let's say, our vision zero plans. And it does not include improvements in livability, equity, improved local environment quality, and enhanced public health. For example, I don't think it considers the impacts of air pollution on asthma or chronic pulmonary and heart disease, which we know are really big impacts of our transportation system now.

But most important thing about this from a policy perspective for cities is that it does include many different strategies that cities can implement in various ways, and includes many kinds of pricing and taxes, ranging from parking pricing, to road or congestion pricing. It includes land use and smart growth policies, includes non-motorized transportation, includes improvements to public transportation, includes ride sharing and car sharing and other community strategies. I think they're referring mostly to carpooling, not to ride hailing services. But you can imagine that some of those results might extend to ride hailing services.

Includes regulatory strategies, operational and intelligent transportation strategies, things that probably have expanded in the last 13 years since the report was written because the growth of telecommunications infrastructure. Just to put this in perspective, this report was written one year after the iPhone was introduced. And yet, we probably all use various mapping applications on our phones every day now to figure out the quickest way to a certain place or to work.

And finally, the capacity expansion bottleneck relief, multimodal freight sector strategies, I would argue, are things that, as urban planners, we don't look at very often. It also considers different levels of deployment. Expanded current practice focuses mostly on major metro areas. And aggressive level of deployment does this sooner and more broadly geographically deployed through smaller or medium-sized metro areas. And the maximum effort assumes the maximum national, regional, and local focus on trying to reduce greenhouse gas emissions.

Finally, they categorize these things into different strategy bundles. They look at near-term early results. They look at long-term maximum results. They look at land use, transit, and a non-motorized bundle. And they look at a system driver-- system and driver efficiency bundle, a bundle that improves transportation facilities themselves, and finally, and importantly, a low-cost bundle, looking at what are the lowest cost things we can do to reduce greenhouse gas emissions.

So if you look at some of the results, they measure things against the study baseline. They do a sensitivity analysis according to different kinds of assumptions around fuel prices, vehicle miles traveled, an Obama administration proposal at the time. Crucially, though, and this is something that we found a little depressing when I taught this report in class, is that if you look at these six strategy bundles at the maximum and aggressive deployment levels, you can see that the most max, the maximum range full of national, regional, and local effort only gets this about a 24% reduction in greenhouse gas emissions.

The report was written in 2009. They had a 4% decline already baked in-- I assume, largely from vehicle efficiency standards. But if we do everything in the report that they analyze, which we'll talk more about, you only get to a 24% reduction.

Of course, a 24% reduction in transportation, which is about 30% of our total greenhouse gas emissions, is not nothing. That's about a 7% or 8% reduction in our total greenhouse gas emissions by 2050. But obviously, a small drop in the bucket towards where we need to go in 2050.

And if we just maybe highlight that again, you can see that the maximum level of deployment reduces millions of barrels per year by 11. Maybe 110 to 470 million barrels per year. But the consumption in the US is 5.7 million barrels per day. So in other words, this range is only about 19 or 82 days per year in the transportation system alone. These assumptions, of course, could have changed in the last 13 years-- the last 13 years, but I think this just highlights that transportation is a really hard to decarbonize sector.

Now, there's one point that I want to make about all of these different strategies. And I think it's an important point to make. Which is, we can have these six different approaches to trying to reduce our greenhouse gas assumptions in this first column. They all have varying degrees of greenhouse gas reduction. They also have positive implementation costs. You can see they cost different amounts.

The system and driver efficiency, perhaps, efforts are relatively expensive. The long-term maximum results and facility pricing are relatively expensive. But the point is all of the implementation costs are positive, but the changes in vehicle costs are all negative and much larger.

Which is to say that vehicle costs in footnote B says, it's the estimated cumulative reduction in the cost of owning and operating vehicles from a societal perspective, which would result in reduction in vehicle miles traveled and fuel consumption. In other words, even though the implementation cost for all these strategies is positive, the change in vehicle costs is negative and much larger. Which means if you take the implementation costs minus vehicle costs, you can see, in almost all these cases, five out of six cases, we actually save a lot of money over the forecast for these different strategies. This is at the aggressive level of deployment.

If you look at maximum level of deployment, again, five out of these six strategies are actually negative cost. So if we look at the greenhouse gas reductions that results, they actually have a negative cost per ton. Which is to say that not only do you save money, you can also reduce greenhouse gas emissions. And that's true for five out of the six strategies at the aggressive deployment level, and then, it's true four out of the six strategies at the maximum deployment level.

This is not taking into account the cost of actually reducing carbon or the social cost of carbon. For example, the net cost of reducing a ton of gas emissions in the near term or early results is negative $410 per ton at maximum deployment level, which means that we would actually save $400 for every ton of greenhouse gas emissions we're saving. That's not even including excluding the $51 the federal government says every ton of greenhouse gas emissions costs us, or the $150 that the most recent studies say is the social cost of carbon. So this is to say that we should try to do the negative cost stuff because we're going to reduce greenhouse gas emissions and save ourselves money in fuel anyways.

Just to show you this graphically, this is for the near-term early results bundle, aggressive deployment. It costs about $20 billion in 2008 to implement, between 2008 and 2050, but you can see the vehicle cost savings is worth that. At their high point, they're about five times more than the implementation cost that year. And even at their lowest point, in 2050, they're about four times the operating cost.

This is to say, if we make policy changes and change infrastructure, we can reduce greenhouse gas emissions and save money in the long term throughout almost the entire life of this bundle. And if you look at what that bundle is composed of, you can see that these different categories. This is composed of pricing strategies, for example, a price on parking in central business districts, a price on parking for free private parking, residential parking permits, and congestion pricing.

Public transportation strategies, we have commuting strategies, regulatory strategies, system operational strategies, and multimodal freight strategies. All of these things together get us a 14% decrease in greenhouse gas emissions from just the near term or early results bundle. But also, crucially, it is saving us money in this bundle throughout the lifetime of the bundle.

If we do the long term or maximal results bundle at aggressive levels of deployment, you can see that our implementation costs start off much higher, around $80 billion. Goes down to $60 billion a year in 2050. But our vehicle cost savings are still almost a factor of 2 or 3 higher than our implementation costs, which is to say that we are going to save money through the lifetime of this analysis.

And you can see that to get to our maximum level of deployment, that's our 24% reduction, we have to do many more things over the long term to get our maximum results. I'll let you dive into the report to understand what some of these policies are. But all these policies are the things that you can work on in your careers.

If you look at the same bundle in terms of the graphics, you can see that it starts off-- I think this one might actually be repeated from before. Apologies. But the crucial thing is here's all of the strategies that comprise this bundle. And you can see the land use transit and non-motorized application bundle, which is something that planners focus on quite a bit.

The implementation costs are slightly higher than our near-term results, but, again, our vehicle cost savings are roughly two or three times what our implementation costs are. And you can see that there are many things that urban planners love, ranging from pricing strategies, to transportation, to land use and smart growth strategies, to public transportation strategies, to regulatory strategies, and so on. So this brings you to the idea of marginal abatement.

This is a very famous graph done in 2008 by McKinsey. McKinsey didn't invent the marginal abatement cost curve, but they certainly popularized it in a 2008 report that was studying the cost to reduce greenhouse gas emissions across the US economy. Arguably, the 2008 report by McKinsey inspired the Moving Cooler report in 2009.

But the key thing here is that what you do is you graph on the horizontal axis the potential savings in terms of gigatons of carbon dioxide equivalent per year. The width of each of these bars tells you how much potential is associated with each of these different technologies or policies. The crucial thing here is on the vertical axis. You can see that some things cost money to reduce a ton of greenhouse gas emissions, and some things, like our Moving Cooler report, are negative. You actually save money and you reduce greenhouse gas emissions.

My unsolicited career advice to all of you is that you want to be on the left-hand side of this curve. The left-hand side of the curve are all things that are essentially free for people, and they achieve our environmental goals. So it is much easier to sell, let's say, changes in commercial buildings and residential buildings and fuel economy packages than it will be to do things like concentrating solar power, solar CSP, which was a very hot topic in 2008, but we've proven over the last 10 years that those costs have never gone down as much as solar panels have.

And this is probably out of date. Distributed solar PV has become much cheaper. But even if you compare this to solar, distributed PV is relatively expensive compared to utility scale photovoltaics. But of course, those things are still more expensive than residential water heaters. Not the sexiest topic, but a place where you can actually have significant impact if it has a negative cost and it has a significant potential.

Combined heat power, residential building lighting, these are fundamental changes we can make in buildings which we'll talk about in the next few lectures. The point of this is that you can be trying to do things that have negative costs and reduce greenhouse gas emissions, which is something we can analyze on the Moving Cooler report.

If you look at the Moving Cooler report, around page 47 or so, you can see different categories of how much potential there is to reduce greenhouse gas emissions. This is the expanded, aggressive, and maximum levels. And you can see, on a categorized basis, that pricing strategies are basically as much as everything else put together. However, on a per unit basis, or on a cost basis, you can also see that the negative costs are red.

Our public transportation strategies, as we talked about in class, are relatively expensive. They don't always recover. They don't have fare box recovery or they don't cover their full cost through the fare box. But we may invest in public transportation as a public good.

It also has benefits and livability and safety and access, the things that this report doesn't necessarily include. But it's also worth noting there's lots of other things we can do that essentially have a negative economic cost. They probably have beneficial costs in terms of safety and health. They're just not included in this report.

So everything here in red at almost all levels of deployment is a negative cost, and they reduce greenhouse gas emissions. This is a cost of-- a cost of reducing a ton of greenhouse gas emissions. You can see that, in the data analysis, I looked at the total reduction divided by the net cost.

And if we break it down into the various strategies, you can see that the category of system of operations and management is composed of active traffic management, integrated corridor management, and signal control management. These all have a maximum level of deployment, a cost to reduce a metric ton of carbon dioxide equivalent. These are all positive costs. You can see that if we move one page down, you can see lots of other things have negative costs. I would argue to you negative costs are the things that should be easiest to sell in your career.

And, of course, if you look at something that is not very glamorous, incident management, incident management looks like, on a per cost basis, basically almost the equivalent of everything else put together. So I would argue that this is the first thing we should be doing to try to reduce greenhouse gas emissions.

If we look at the expanded, aggressive, and maximum levels of effort, just to talk about it a little bit more, expanding current practice is basically in large urban areas that already have transit, medium urban areas that have transit, and small areas that have transit already. And then, in the future, we'll try to improve the larger urban areas, medium urban areas, and small urban areas that have transit.

We want to be more aggressive, we'll start doing this faster for all these categories and bring them up in time. And a maximum effort would have been to start 10 years ago, in 2010 or so, to try to do all of our metro areas or all of our urban areas with these transportation interventions. I finally got around to making a marginal abatement cost curve from the Moving Cooler report itself. You're going to see these nine different categories or strategy types.

I think there's a very thin sliver over here is probably the incident management I mentioned before. And you can see the system operations and management strategies are relatively cost effective. They're negative cost, but have really large potential.

You can see that much of our negative potential here is composed of pricing strategies, which is going to be politically very difficult, but worthwhile. But we can also get a lot of changes in our transportation system emissions simply by changing our regulatory strategies. And I'll let you look at the report to see what those are.

We do love our land use and smart growth strategies. It's the very small box here. And public transportation strategies, as I said before, tend to have a positive cost, but actually do reduce greenhouse gas emissions. But you can see that all the things we often talk about as urban planners are relatively small in potential. There's lots of things we can do over here in pricing strategy and regulatory measures, but I would argue we don't talk about it enough in urban planning.

HOV, carpool vanpool commute strategies, this blue box right there in the middle. We go to an aggressive level, I've replotted this with the social cost of carbon at $150 per million-- sorry, $150 per metric ton of carbon dioxide equivalent. You can see that, in almost every case, everything is cheaper than letting greenhouse gas emissions continue unchecked, or everything is cheaper than climate change.

So from a social cost of carbon perspective, we should just make all these transportation efforts as soon as possible. And, of course, at the maximum level, you can see that, at the maximum level, some things-- I think that's incident management-- is incredibly beneficial from a cost perspective and a greenhouse gas values perspective. But pretty much everything else here is small.

And the point is, at a maximum level, everything is less than total cost of carbon. Again, a good argument for trying to reduce greenhouse gas emissions anyways. Just to bring us back to the Daniel Sperling identity, I said before, this is-- I want to highlight the different parts of the system and how to break down the system. There's mobility, the demand we have for transportation, vehicle miles traveled, there's the vehicle energy efficiency, and there's the carbon intensity of the energy itself.

Greenhouse gas emissions per unit of energy. And that is what gives us greenhouse gas emissions. The reason why I say that is because if you look at the existing Sankey diagram, you can see that, in the US now, we have a very small fraction of hydrogen production and it almost entirely goes to industry. Almost all of our transportation energy comes from liquid fuels, petroleum, and petroleum sources.

But if you want to reach a fully decarbonized economy-- this is the Williams et al. 2020 paper. For 100% renewable energy matrix, it basically forecasts that transportation will come from liquid fuels that are derived, originally, from hydrogen. And from that hydrogen, with renewable resources like solar and wind.

How are we going to get there? And what does that mean? The MIT team led by Steven Barrett in Aero Astro, and Bill Green in Chemical Engineering, put together a proposal for the Climate Grand Challenge. They called it the tough-to-decarbonize transportation initiative in 2021.

The key finding from these system engineers and from these chemical engineers was that we're going to need new vehicles, new fuels, and an entirely new hydrogen system in order to decarbonize transportation. Below greenhouse gas carbon-based fuels, the main challenge is the huge scale of fuel production needed. All of our low greenhouse gas fuel options, even biofuels, depend on a huge scale production of low greenhouse gas hydrogen. And the cost of low greenhouse gas hydrogen is often the largest part of the cost of the finished low greenhouse gas-emitting fuel.

And they find a number of key findings in the executive summary. First, long distance vehicles in the tough-to-decarbonize transportation sectors, aviation, shipping, and trucks. All those long distance vehicles carry their own energy, so the energy density is crucial. But more weight and more volume of a fuel or battery you carry reduces the payload for the vehicle, which is the purpose of the trip in and of itself.

The alternatives we have with hydrocarbons are two to three times heavier and require greater volumes. They also point out a major challenge is going to be the scale of achieving this fuel infrastructure. Today, only fossil fuels are available at the huge scale needed, about a billion tons per year. And realistically, only a few low-carbon alternatives could reach the needed scale by 2050.

Existing vehicles are all designed to use hydrocarbon fuels, so we either need a carbon fuel that doesn't increase gas emissions, a, quote unquote, drop in fuel, or we make a liquid fuel like gasoline from renewable resources, like solar or wind, instead of pulling it out of the ground. And we're also going to need new vehicles, or we need new vehicles to use new fuels. Those vehicle lifetimes are long, 20 to 30 years, and new vehicle development is very slow. So if we want to achieve decarbonization by 2050, we need to start developing new vehicles now.

The good news, as you know from the news, we have many new vehicles, many new trucks being developed now. We probably arguably have fewer options for shipping and aviation, so shipping is one sector that seems to be quite engaged in reducing its greenhouse gas emissions. The cost of the fuel itself is a significant part of the total cost of transportation services. The fuels for the sector currently costs about $1,000,000,000,000 per year.

And expensive infrastructure adds additional costs. So if we want to build a new fuel infrastructure, we're going to need new infrastructure, and we're going to have to achieve that on a cost competitive basis. And of course, there's the practicalities of fuel infrastructure.

Room temperature liquids are much easier to distribute and store than gases or solids. Fast refueling and recharging is important for some vehicles. On a very practical level, that new fuel has to be available at 800 ports, 17,000 airports, and more than 100,000 truck stops in the US.

Another summary slide from these sectors that this team identified as tough to decarbonize, trucking, shipping, and aviation. They all constitute about 1 to 1.25 gigatons per year. That's about 3.25 gigatons a year, about 1/10 of all of the greenhouse gas emissions for the world.

You can see that all these vehicles have very different vehicle intensity of greenhouse gas emissions per use. The engines themselves are different. They use different fuels. And they have very different power requirements. It requires a lot more power to lift a plane into the air than it does to move a truck along a road or a ship through water.

The state of electrification is that, trucking, we can achieve at relatively high cost. It looks very challenging for shipping. And for aviation, it's basically been deemed fairly impossible over large distances because the batteries themselves weigh so much, they would displace the passengers, or simply weigh too much for the plane at all.

Fuel cell options where we use a chemical battery are relatively high cost for trucking and shipping. Not possible for aviation. If you summarize these things, we have a few different viable pathways that we have to focus in on.

We have many different viable pathways for trucking. We have a few options for shipping, carbon-based fuels, ammonia or hydrogen. And for aviation, we need the energy density of carbon-based fuels. They have low weight and low volume compared to how much energy carbon-based fuels pack in, so we need to think about aviation fuels that will be low carbon in order to continue flying.

This is to point out that, again, if you look at the Moving Cooler report, you look at these tough to decarbonize transportation sectors, urban planners can do a lot. They have jurisdiction. They have authority to help plan new infrastructure. They have authority to plan freight infrastructure, which we don't look at very often. But I would argue to you that this is kind of an unexplored area for urban planners to try to affect.