[SQUEAKING][RUSTLING][CLICKING]

DAVID HSU: Hi, everyone. Welcome back to the MIT Lecture Series on Urban Energy Systems and Policy. Today, we're going to be talking about cities and personal transportation, the first of a number of lectures on transportation and energy systems in cities. Again, if you've been watching these lectures, my name is David Hsu. I'm an associate professor of Urban Studies and Planning at MIT.

Today, we're going to talk about energy and personal transport. Again, the materials assigned for the lecture today, a lot of them are available online if you search around. And the main questions I want to talk about today are, why is personal mobility important in terms of energy.

We're going to talk about why or whether or not electric vehicles are more efficient than internal combustion engine cars. We're going to ask by how much, and is this the same in all places. We're going to talk about other kinds of vehicles such as bicycles, electric bicycles, and scooters.

And one little chapter of our talk today will be on what policies can be used to move the international vehicle market and to sway international automakers. One answer is what Mary Nichols and the California Air Resources Board have done in California. And we'll talk a little bit about what the Inflation Reduction Act does to encourage electric vehicles and how its policy incentives work.

And next week, we'll start talking about, what about larger infrastructure? How do roads, fueling infrastructure such as oil and electric grid, play into the energy use of transportation? And so we'll just start by talking about why mobility is so important.

Mobility is, essentially, a superpower. Mobility gives us the ability to access jobs, housing, services, and leisure. The more mobility we have, the more ability we have to dis-aggregate all of these things we want to access.

If you live in a dense, compact neighborhood, your job, housing, and services could be in the same place. But you may want to travel around the city, hopefully by easily-accessible modes of transportation. Or if you live in a place that has a very low population density, your job, your housing, your services, your leisure opportunities may be far-flung, like in many US cities.

But it's also particularly important to note that enabling mobility in cities is particularly hard due to population density. If you want to build good infrastructure to enable mobility, you have to plan that. If you are trying to retrofit cities with new infrastructure that enables mobility without inducing, let's say, more traffic or more congestion, you also have to think very hard about how to retrofit cities that already have a certain level of population.

And so there's a nice way to think about the carbon emissions from personal transportation. Daniel Sperling at UC Davis, also a member of the California Air Resources Board, has a nice little identity, or a nice way to think about this. It's an identity that goes like this.

You measure mobility in terms of vehicle miles traveled. That's essentially indication of demand. You multiply times vehicle energy efficiency, which is measured in terms of energy used per vehicle mile. That's a measure of how efficient the technology is. And you multiply times the carbon intensity of the energy going in, measuring, essentially, the carbon intensity of the fuel going in, which is measured in terms of greenhouse gases per unit of energy.

If you multiply all these three things together, you get greenhouse gas emissions. But this is a way of decomposing greenhouse gas emissions to say that it matters how much we demand in the first place, in terms of mobility. It matters how efficient our technology is, in terms of turning energy into transportation.

And then it matters how much-- what the fuel intensity of our energy going in is. In other words, how much emissions do we incur to create the fuels for the technology to satisfy our demand? And so another way to answer what the importance of energy is, or why energy and transportation are linked, is to go back to our helpful Sankey diagram. I think I showed you this in a few lectures past.

This is the estimated US energy consumption in 2021. Roughly 97 quads, which are quadrillion BTUs. It's a helpful number, because the US economy has roughly been at around 100 quads. So when you look at the source energy used on the left, over here, you can think of most of these numbers as roughly within about 3% of the percentage of the total source energy, or primary energy for the US economy.

When you look at these final sectors of use, you can get a sense of how much energy is converted from the primary sources into final consumption. And of course, we have intermediate steps like generating electricity for lighting. At the same time, we also have this kind of gray bar, which breaks down the total amount of energy that's rejected through heat loss versus how much is actually converted into the services we want. So energy services are the services or final consumption we want.

In order to do that, we actually have some rejected energy, mostly energy that's lost as heat as we combust fossil fuels. And so just to understand again, to break down the numbers on the Sankey diagram and understand why energy is so important for transportation, you can see that the vast majority of petroleum here goes towards-- about maybe 2/3 of it or 3/4 of it goes to transportation, 1/4 of it goes to industrial uses.

And then you can see that of the energy that went to transportation, a lot of it gets rejected as heat, basically out of the tailpipe of the car, or out of the smokestack of a power plant if we're generating electricity. And so actually, a very small fraction of the energy for transportation is actually the service we want of moving people and goods. So we want to look at the percentages of how this plays out in terms of transportation. You can see the percentages for transportation are relatively unique. And we'll calculate some of those directly using the numbers off the Sankey diagram.

And so if you are seeing this for the first time, I encourage you to flip back and forth between these two slides and spend some time figuring out where the blue numbers come from and how we do these calculations. If you want to see how much petroleum is of the total amount of energy in the economy, it's 35.1 quads divided by 97.3 quads total. It means that petroleum is 36% of all US primary energy.

If you want to understand the percentages of petroleum used in transportation, it's about 24.3 quads out of 35.1 quads of petroleum total, meaning that, essentially, about 70% of all petroleum is used for transportation. As you can see from our Sankey diagram-- I'll flip back here. You can see that's fairly unique among all the energy sources here on the left.

Now, we know that we've been talking about the energy implications of petroleum for many years. Not only in terms of our reliance on overseas imports, but more recently, in terms of the greenhouse gas emissions implications. And also in terms of energy security. Where do we get this energy from?

And, of course, a more recent story is that the US has become one of the largest petroleum producers in the world also. So we are also contributing petroleum to the world, which has definite implications for our production and how much greenhouse gas emissions we're exporting to the rest of the world. If you look at the total amount of energy in transportation, you can see that we use about 26.9 quads of energy, divided by 73.7 quads of all sector energy use. It means that transportation is one of the largest energy-using sectors. It represents 36% of all energy use.

And in terms of energy services, we only get 5.65 quads out of 26.9 quads input energy, meaning that only 21% of the energy that we put into transportation becomes the final service we want, the actual mobility or the actual movement of goods and services. And so, as I pointed out before, the rejected energy, that's all mostly heat energy that goes out of the tailpipe of internal combustion engines. 21.2 quads divided by 26.9 quads means that we basically wasted 78% of our energy inputs into transportation.

And so thinking back to the Sperling's identity, weighing demand and efficiency of vehicles versus the carbon intensity of energy, we can use all these percentages to think about how do we perhaps reduce our demand, how do we perhaps increase the efficiency of our vehicles, and how do we reduce the carbon intensity of our fuels. So this is why it's exciting to talk about electrification. And this is why I'd start with electrification or building the energy system from the bottom-up.

When I started teaching this class around 2017, *The Economist* had this cover on the left declaring the internal combustion engine "Roadkill." And one of the figures they used to support this were the estimates showing that all of these major forecasting organizations, Bloomberg New Energy Finance, OPEC, the Organization of Petroleum Exporting Countries, and ExxonMobil, had all increased their electric vehicle sales forecasts. Of course, Bloomberg New Energy Finance has been perhaps the most aggressive forecast, or most aggressive forecast for the number of electric vehicles. But you can see between 2016 and 2017, both OPEC and ExxonMobil, two entities that probably are not welcoming the adoption of electric vehicles, also increased their sales forecasts.

If we look more recently at Bloomberg New Energy Finance's electric vehicle outlook in 2022, you can see that it further increased their economic transition scenario, or their estimates of the global long-term passenger EV fleet by market. And you can see that their estimates are now up to around $700 billion electric vehicles, when a few years ago, they were at $500 million. And if you look at their forecasts of what the global passenger vehicle fleet by drivetrain will look like on the right-hand side, they show that internal combustion engines, this gray block, will decrease-- will increase slowly to 2020 or so, and then start decreasing pretty much around now.

They show that hybrid vehicles will increase, but be a relatively small share of our future drivetrain fleet. Battery plug-in hybrids, and fuel cell vehicles, barely. You can see them here. But the majority of vehicle growth will be in battery electric.

Until by 2040, there will be as many battery electric vehicles as there are combustion engine vehicles. And this, of course, depends on Bloomberg New Energy Finance's forecast and some of their modeling. But it's also worth pointing out, and I like to point this out every year since 2016 or 2017, that electric vehicles are still very new technologies. They're still very new products in a consumer marketplace.

The Bolt electric vehicle was one of the first low-cost electric vehicles that was long-range. It was only introduced in 2016. They beat Tesla to the market by one year, when Tesla introduced their first, I think, sub-$35,000 or sub-$40,000 model, the Model 3, in 2017. It is worth pointing out most automakers have yet to introduce electric vehicle models, even though if you look at *Car and Driver Magazine,* you'll see that 50 or 100 new electric vehicle models are expected to come out in the next few years. But it's worth looking at how quickly electric vehicle sales are growing as a share of new cars.

If we compare the first half of 2021 numbers to the first half of 2022 numbers, globally, electric vehicles went, from last year to this year, from 4% to 5% of new car sales to 12%. In Germany, they went slightly up, from 12% to almost 14%. In China, they went from 12% to 20% of new car sales.

In the US, they almost doubled, from 3.6% to 6.2%, despite declines in the sales of other vehicles probably due to price inflation and rises and vehicle shortages. But despite all these problems, electric vehicles have increased their market share of new car sales. So this is what we'll start by analyzing private vehicles, a.k.a. personal transport, and understand them in terms of their energy consumption in terms of energy per person, per kilometer, or per 100 kilometers.

So this is a figure from MacKay 20.23. The vertical axis is the energy consumption per person per distance. And the horizontal axis is the speed in terms of kilometers per hour. And you can see if we were to compare, let's say, two of the waterborne transportation modes, the Vancouver SeaBus, a SeaBus that I've ridden quite a bit, is compared to a catamaran.

And you can see that the energy consumption of the catamaran is actually higher, though the speed is higher. I assume that this is a motorized or fueled catamaran rather than a sailing catamaran. And you can see that the energy consumption for the SeaBus is relatively lower, because it's lower on the vertical axis. Of course, it could be because the SeaBus has a limited range and moves about 400 people at a time.

Now, if we look in terms of the airborne modes of transportation, you can see that a turboprop plane has much lower fuel consumption than a Boeing 747, even if the Boeing 747 is full. And, of course, lower than a Boeing 747 if the Boeing 747 is not entirely full. Of course, the most useful part of this graph, I think, is comparing the different modes of transportation. For example, whether or not-- what the energy consumption of a car is versus public transportation.

So if you look at a car that is full, it has roughly about 20 kilowatt hours per 100 kilometers per person. The underground system looks like it's about, I'd say, 15 or 16 kilowatt hours per 100 kilometers per person. Of course, if the underground train is full, that drives it very low, to about 4 kilowatt hours per person per 100 kilometers.

And, of course, walking and cycling is still lower, but the speeds are lower. And so you can start to see this trade-off between the speeds we would like to attain either for short distances, in terms of walking or cycling, or long distances, like high-speed trains. And, of course, you can see why, in many cases, high-speed trains are out-competing short-haul aviation. In North America, we tend to use turboprop planes for short-haul aviation instead of large jets like a Boeing 747.

But also, if you look at-- compare that to an electric high-speed train, the electric high-speed train has much lower energy consumption than a turboprop plane. This is essentially why China building a large high-speed rail network has apparently wiped out the entire short-haul aviation market. Of course, you can make do with things like a bus or a coach that is full, also has much lower energy consumption than individual cars. But you can see that trains can largely outcompete-- trains, electric trains, or high-speed trains can outcompete buses quite easily. Of course, they have a larger upfront cost in terms of land, and building the rails and the electrical grid required to support those trains.

So if we use graphs like this, you can compare not only the energy consumption, but the speed that we would like, in terms of to achieve mobility. And so here's a-- kind of a bit of a teaser that I put in the problem set. Let's ask a simple policy question.

Which vehicles should we focus on making more efficient? In terms of policy, we want to target our policies well. We want to spend our time as government officials having the most impact for the time we spend. So should we make SUVs slightly less gross, maybe increasing their average 11 miles per gallon to a whopping 13 miles per gallon?

Or should we make passenger cars super-efficient? Let's say going from the fleet average for passenger cars, from 29 miles per gallon, maybe changing them to hybrid drivetrains that get 49 miles per gallon. So if we use some of the calculations we learned in MacKay chapters 3 and 20, you can see that actually going from-- if we flip this over, in terms of 11 miles per gallon, that has roughly 0.091 gallons to go per mile.

And if we flip over 13 miles per gallon, that basically implies that 0.077 gallons per mile. And so this is the point from the MacKay reading. We want to look less at miles per gallon, which is an indication of how many miles you can go in a given amount of fuel, and instead look at how much energy are we spending to go a certain distance. This emphasizes the service we want to get, which is mobility.

So we take this number, flip it over, and we measure how much energy we need to go a certain mile. And so if we go from a gross SUV from 0.91 gallons per mile and make it more efficient, we go to 0.77 gallons per mile. If we do the same thing for passenger cars, we go from 29 miles per gallon to 0.34 gallons per mile. And we go from 49 miles per gallon to 0.20 gallons per mile.

But this is a bit of a brainteaser, or I guess a trick question. Because the difference between both pairs of vehicles is the same. We're actually going-- improving them by 0.14 gallons per mile. This is just a kind of trick question I want to use to illustrate a point about consumers' perceptions versus misperceptions of energy costs.

This is a paper by Hunt Alcott in the *American Economic Review.* And what this is called is the "MPG illusion," in which most people think intuitively that automobile fuel costs scale linearly in miles per gallon. When, in fact, what we care about is the amount of energy we spend on service, which is going-- how many gallons of gasoline do we need to go per mile, or how much fuel do we need to go per mile of service. And so this is just the indication that this is a systemic bias or a systemic misperception that people have about energy costs.

So let's focus on the powertrain options we have to achieve the service we want, which is mobility. Internal combustion engines. This essentially is where we burn fossil fuels to move the car.

We have hybrid drivetrain, which have been around for, I think, almost 15 or 20 years now, where fossil fuels move the car, but we integrate a small battery to store the power from braking to move the car. This is the well-known Prius that's been around for many years. We have plug-in hybrid electric vehicles, or PHEVs for short, where we have a larger battery that moves the car up to 20 or 40 miles. And then we have a fossil fuel engine still in the car that's used to extend the range of the battery, and you can charge the battery off gas if you run out of electricity.

And, of course, we have fully battery electric vehicles where the battery moves the car 200 or 400 miles. These electric vehicles have drastically less maintenance because an electric motor is easier to maintain than an internal combustion engine, and they're less mechanically complex. But they also, as we saw in the readings from the Miotti et al. paper or the Kidner article, Kidner chapter, the cost of electric vehicles largely depends on battery costs. Almost 35% or 40%, I think, of the entire cost of the vehicle is simply the battery.

This is also why Tesla has built a gigafactory to churn out batteries at lower cost at higher volumes. Tesla believes, and I think they're being proven correctly, being proven right, that if they produce batteries at very large volumes, they'll learn about how to make the batteries more efficient, they'll produce a lot more batteries and drive the cost per unit down. Therefore, that will lower the cost of the cars they're selling, because most of the cost of the car is the cost of the battery. Or much of the cost of car is the cost of the battery.

Just to show you what these different powertrain options look like, this is a diagram from the Kidner chapter that I assigned and referenced at the beginning of this lecture. You can see a battery electric vehicle has a fairly simple drivetrain. It has a charger going to a battery, going to a power converter, to an electric motor, to the transmission.

A series electric vehicle has not only a battery, a power converter, you can generate power from the fuel tank, the internal combustion, and convert power into the electric motor, which goes to the transmission. A series plug-in hybrid electric vehicle has the ability to plug into the wall, power the battery, power the converter. Or you can also put gas into a fuel tank that drives an internal combustion engine that runs a generator that creates electricity, then goes into your transmission.

And then you have a fuel cell electric vehicle, where the fuel cell, essentially, is another way of storing electricity. Whether from gasoline, or from natural gas, or hydrogen. There's a fuel cell stack.

The fuel cell stack can be used to run a generator, which creates electricity. The battery can also be charged from outside of the vehicle, which all drive the transmission, again. So this is to say that there's many different possible drivetrains for the kind of mobility services you want in passenger vehicles.

Just to do a few simple calculations to illustrate the amount of energy we need per service or per distance we want to go. For an internal combustion engine that gets-- an SUV that gets, let's say, 22 miles per gallon, that's kind of generous for most SUVs, to be honest, we have the energy density of the fuel, which is 10 kilowatt hours per liter. That's the figure from MacKay.

We multiply times the inverse of gallons per 22 miles. We convert liters to gallon. We convert miles to kilometers. And we multiply times 100.

So we get 100 kilowatt hours per 100 kilometers. This is simply dimensional analysis. So you can cross out liters top to bottom. Cross out gallons top to bottom. Cross out miles top to bottom.

I just want to show you how to convert some of these metric or SI units to imperial numbers that we might be more familiar with. Imperial, or US system of measurement. If we take the same calculation for a Toyota Prius, which is a hybrid vehicle, we put in the energy density per volume of the gasoline that goes in. But as we know, Priuses are drastically more efficient because they have a hybrid battery to help them store energy from braking.

So you take the 10 kilowatt hours per liter divided by 56 miles per gallon. So this 56 decreases the energy consumption by a factor of 2. All the other factors are the same. And you can see that we get to 43 kilowatt hours per 100 kilometers traveled for our Prius.

And, of course, EVs according to MacKay's research assumption in 2009, get about 100 kilometers for every 15 or 20 kilowatt hours of energy going in. So if you want to do a simple summary of what this means, you can see that there's multiples between these different vehicle types. You can see that the difference between SUV versus an electric vehicle is 5 to 7 times more efficient, an electric vehicle. Even between a hybrid vehicle and an electric vehicle, it's 2 to 3 times more efficient.

So this is our argument for electrification. This is why electric vehicles are so efficient and why we're trying to pursue electric vehicles. If we look at the Miotti et al paper, in figure 1, you can see that basically every single battery electric vehicle, symbolized here in the yellow envelope, is lower energy consumption than pretty much every hybrid vehicle. Lower, sorry, vehicle and fuel lifecycle greenhouse gas emissions, which are very closely associated with how much energy they consume.

And you can see that there's envelopes stretching along the horizontal axis, because we know that some of these cars are more expensive than others. An electric Chevrolet Spark is much cheaper, in terms of vehicle, fuel, and maintenance costs, than a Tesla Model S. Of course, the Tesla Model S is more expensive, but has much lower lifecycle greenhouse gas emissions than pretty much all the fuel or hybrid vehicles out here.

You also might notice that all of the gasoline combustion engine vehicles here at the black dots do not meet our 2030 targets for the Paris Climate Agreement. Some of our hybrid vehicles do get under the 2030 target, and pretty much all battery electric vehicles meet our 2030 targets, but do not meet our 2040 targets. In fact, if you look at all the vehicles on this chart, there are no vehicles that meet our 2040 or 2050 targets.

We still have some time before those years. We have 18 years until 2040, so we can still develop new vehicles that hopefully meet those requirements. But right now, it's worth saying that none of our vehicles today that are commercially available meet our 2040 or 2050 Paris Climate Agreement targets. That is also-- those are capital assets that individual consumers and countries will have to invest in so that we can meet our Paris Climate Agreement targets.

If you look at all the ways that we can try to improve our existing powertrain or drivetrain technologies, on the graph here, figure 4 from the Miotti et al. paper, you can look the average emissions based on 2014 models in terms of grams of CO2 per kilometer. And you can see all the different vertical bars represent different drivetrain or powertrain technologies. And what we can do-- what this graph tells us is that if we do a series of things to try to improve each technology, how far can we push these technologies.

So we could try to start with the sales-weighted average of 2014 models. These are new cars or basic trims. We can, for each of these technologies, try to downsize to compact cars.

In the electric-using technologies like electric vehicles or plug-in hybrids, we can increase the amount of low-carbon electricity available, we can make the maximum efficiency improvements. And in some cases, we could try to use best-case biofuels. And, of course, the best case for all these technologies is we do all of the above things. And you can see that there's fundamental limitations to different powertrain technologies.

For internal combustion vehicles, internal combustion vehicles that use gasoline, we can only get better than our 2030 targets, but we can't get to our 2040 targets. For internal combustion engine vehicles that use E85, that's ethanol fuel, 50% ethanol fuel, I think, you can see that we can barely meet our 2040 tar-- 2030 targets. Sorry, 2040 targets. But we can't meet our 2050 targets.

It is possible that internal combustion engine vehicles, such as diesel, to get below our 2050 targets if we pull out all the stops. Of course, that ignores the fact that diesel has severe air pollution impacts also, something seen in many European cities. The reason why we see, let's say, a lot of old statues degraded, or their features are starting to be worn away is from diesel fumes. They also have severe health impacts.

If you look at hybrid electric vehicles and plug-in hybrid electric vehicles, they are much better, but barely get to within range of our 2040 targets. The only technology here that can exceed our 2050 targets are battery electric vehicles or fuel cell vehicles where the vehicle-- where the energy is from electrolysis, where-- in other words, we use renewable resources to create hydrogen. And the hydrogen used is used to power fuel cell vehicles.

Fuel cell vehicles are a technology that's being tested in the Toyota Mirai, in pilot sales of the Mirai in places like California. They have not been terribly popular yet, and there's a real question if they will ever become as popular as battery electric vehicles, which are taking off very quickly, as I showed you on previous slides. So here's the fundamental question.

If we're looking at MacKay's book, which was written in 2009, let's ask ourselves, have electric vehicles changed since MacKay's book? And we can figure this out by looking at a fairly simple set of numbers that you can look up from any manufacturer, or *Car and Driver Magazine,* or *Consumer Reports,* what have you. Let's look at MacKay's assumptions in 2009.

He assumes that we have about 15 kilowatt hours of energy to get about 100 kilometers of range. That's his estimate. About 15 kilowatt hours per 100 kilometers. His conservative estimate is a higher amount of energy per 100 kilometers. 20 kilowatt hours per 100 kilometers.

Now let's compare this to the Tesla Roadster, which is first sold in 2008. It got about-- has about a capacity of 53 kilowatt hours in its battery. This is one of the small roadsters that Tesla first built. It had a fairly limited range of 220 miles, or 354 kilometers. And that means it calculates almost exactly to MacKay's estimate in 2009, about 15 kilowatt hours per 100 kilometers.

Of course, MacKay's numbers were based on just a few electric vehicles available at the time. Very famously, the Tesla Roadster was relatively expensive. Elon Musk was very clear about using high-cost, almost bespoke-built electric vehicles to subsidize building-- manufacturing of more electric vehicles. So that is exactly what Tesla did.

They built the Tesla S, which is a much larger passenger vehicle. The Tesla X, which was their SUV version. They had much higher capacities, or much larger batteries. They had increased ranges.

But you can see that actually, of all things, they go more towards MacKay's conservative estimate for vehicles. Because they had much larger form factors and much larger weight, they actually required more energy to go the same amount of distance. And you can see their costs were very high. $80,000 for a Tesla S, $83,000, I think, for the base model, the Tesla X.

And you can start to calculate their energy per distance per cost. This is just to show you how you can take very simple numbers and start to calculate a basic metric to compare different models. Of course, the Chevy Bolt, the GM model that I mentioned that was introduced in 2016, had a smaller battery pack. It had a lower range, but started to get closer, again, to the estimate from MacKay in 2009. 16 kilowatt hours per 100 kilometers. But the drastic change from the Teslas was that they only charge $37,000 for the initial model, driving the energy per distance per cost way down.

And if you look at the Tesla 3, which was introduced in 2017, you can see that they have comparable battery packs for both the standard and the long-range versions. They have slightly longer ranges because they've-- comparable ranges to the Tesla Roadster or the long-range model, which has a larger battery pack. But you can see that, fundamentally, the amount of energy used per distance has not changed.

Again, what they're doing is competing in terms of price now, because we're trying to reach the broader part of the market that can afford $40,000 cars rather than $80,000 cars. And you can see that the Tesla basically comes in roughly in the same ballpark as the Chevy Bolt. They are directly competing. The Tesla long-range is more expensive, simply because you're paying for that range, even if the fundamental technology, in terms of energy per distance, is not more efficient.

And, of course, what we're seeing now is manufacturers like Hyundai and Kia, large Korean automakers, starting to crowd into the same market. You can see that they've almost standardized their models on a 64 kilowatt-hour hour battery pack. They're starting to get larger longer ranges with the same sized battery pack because battery technologies have advanced.

But fundamentally, the efficiency of these vehicles hasn't changed that much. It's 17, 14, 16 kilowatt hours per 100 kilometer. What's fundamentally changed is the cost of these vehicles. These vehicles are all meant to be sold around $40,000. And you can see in terms of the energy times cost divided by distance, you can see that their cost is going down, driving this metric lower.

This is where most competition is occurring. But my point is, the fundamental technology under battery electric vehicles has not changed that much over the last 12 or 13 years, simply because they're pretty simple. They have a battery. They have an electric motor.

Depending on how many luxury items or how big the form factor is, that might affect the efficiency. But the fundamental technology is fairly simple. A battery, based mostly on lithium ion cells, driving an electric motor. Some cars might have all-wheel drive with multiple electric motors. They're all roughly the same efficiency. But the cost is going down as we adopt more electric vehicles and as more manufacturers compete in the market.

So one question you might have is, what about the carbon of the electricity that's going to the electric vehicle itself? And this is worth pointing out. It's a question that MacKay answers in his book.

His question is, you've shown that electric cars are more energy efficient than fossil cars. But are they better if our objective is to reduce the CO2 emissions, and the electricity is still generated by fossil fuel power stations? Using McKay's reasoning, again, I encourage you to go back to the book if you haven't read this part, this is a quite easy calculation to do.

Assume the electric vehicle's energy cost is 20 kilowatt hours of electricity per 100 kilometers. That's his conservative estimate. If the grid electricity has a carbon footprint of 500 grams of CO2 per kilowatt hour of electricity, then the effective emissions of this car are 100 grams CO2 per kilometer, which is as good as the best fossil cars in 2009. Fossil cars have unfortunately not gotten that much better since 2009. So MacKay could conclude in 2009 that electric cars are already a good idea, even before we green our electricity supply.

If we look at more recent calculations from the Union of Concerned Scientists, they do a miles per gallon calculation equivalent comparing what the grid energy is, and what the emissions are of the grid energy as a gas mile per gallon equivalent. This is why if you buy a new car, you'll see PGE, or the miles per gallon equivalent for electric cars. But if you calculate it backwards and show what the gasoline miles per gallon equivalent is of the grid electricity, you'll see that places like California or the Northwest, that have relatively low greenhouse gas emissions in the electricity mix, have amazingly high miles per gallon in miles per gallon of gasoline. In other words, grid electricity in California is relatively clean.

That's the equivalent, in terms of greenhouse gas emissions, of getting 134 miles per gallon. So you can basically completely outcompete, by a factor of 4, any fossil fuel cars. Here in New England, we have-- in upstate New York, because of hydropower, they have amazingly clean energy. 255 miles per gallon gasoline equivalent.

Here in New England, we have a 122 miles per gallon equivalent. But the key thing is, even in places like the Midwest, that relies heavily on relatively dirty sources of electricity like coal-fired power plants, you can see that most places in the Midwest get about 60 miles per gallon equivalent. In other words, if you get an electric vehicle, you're getting the equivalent of 60 miles per gallon electricity in terms of greenhouse gas emissions. Only two places in the US, looks like Minnesota and parts of the Midwest, get relatively low greenhouse gas efficiencies from electricity. 41 miles per gallon, 43 miles per gallon.

That's lower than you could get with a comparable hybrid in those places if you simply powered a hybrid from gasoline. But most cars are not hybrids. And the average US efficiency, it's something like 20, 25 miles per gallon. So even in these places, electric vehicles outcompete your fossil fuel car, if not your typical hybrid.

The average for all US electric vehicles is around 93 miles per gallon equivalent. So this is to say that in almost all cases from a-- on a just fuel basis, we have much lower greenhouse gas emissions from electric vehicles. The Miotti paper counted the vehicle and the fuel lifetime carbon emissions. And in all cases there, you also saw electric vehicles were lower emissions than hybrid vehicles or gasoline vehicles.

So this brings me to an article that I wish I'd included in the syllabus, but didn't have time to because it only came out last week or so. It actually came from *Outside* magazine. And the headline is "Why You Should Buy an E-bike Instead of an Electric Vehicle." I have an electric bicycle. I love it. So I guess I'm encouraging you to read this article for that reason.

But also because the article is actually full of calculations for what the cost of ownership is for an electric vehicle. For a lot of people who are considering replacing their current fossil fuel cars, the author, Jill Lindsay, argues that it's much better to actually add an e-bike to your household rather than replacing your current car. You might keep your fossil fuel car. But if you try an e-bike, you might like it so much that you simply leave the car in the garage and only preserve it for long distance camping trips occasionally, like the typical reader of an *Outside* magazine might go on.

I would also argue to you that electric bikes have a lot of advantages over electric cars or internal combustion cars. For example, I do a lot of errands on my electric bike. I never have to park it. I just pull up in front of a store or library, and I knock out six errands in my relatively dense suburb in under an hour.

So I can just cruise around, avoid traffic, avoid parking. That time savings is worth a lot for me as a-- to buy an e-bike. And so this brings me to the idea of two- and three-wheeled vehicles. If you don't know what this is, this is a tuk tuk, a three-wheeled vehicle. Also called a "rickshaw" sometimes.

And you can see, in this particular case, it looks basically like a motorcycle up front. It's got a cargo bed here in *back* where it looks like maybe five or six people could ride or cargo could be carried. If you've ever been to various countries in the developing world like India, or Thailand, or sub-Saharan Africa, or parts of Latin America, you'll see a lot of these two- and three-wheeled vehicles. They're called "tuk tuks" in Southeast Asia.

Here's a picture of a traffic jam in Nigeria. You can see that these are the prevalent form of vehicles. You can see this relatively low-density pickup truck in this traffic jam. You can see one car going the opposite direction in this traffic jam. But the vast majority of vehicles are tuk tuks.

And the reason why this is important-- we go back to the Bloomberg New Energy electric vehicle outlook again. And you can see that two- and three-wheeled vehicles and municipal buses-- this is their actual breakdown of road transport segment progress towards net zero. From what they've forecasted, you can see that two- and three-wheeled vehicles and municipal buses are actually almost on-track to have a net zero scenario, 100% zero electric vehicle share, by 2050.

You can see that 74% of two-wheelers will be zero-emission vehicles. 94% of three-wheelers will be electric vehicles. And essentially, with 1.1 billion of these vehicles already on the road, 3.8 million municipal buses on the road, we are almost on track to hit our net zero scenarios.

Where we need to do more work is in terms of passenger vehicles and light commercial vehicles, the kind of vehicles that Americans typically tend to drive. And we need to make a lot of effort in terms of getting to net zero emissions from medium and heavy commercial vehicles. As we know from planning cities, if we want to have more two- and three-wheeled vehicles in developed countries like the US, or low-density countries like the US, we need to improve our biking infrastructure, or infrastructure in terms of allowing these two- and three-wheeled vehicles.

Municipal buses are already a cost-effective alternative for transportation, relatively convenient to charge, because they go on the same route every day. But we know that buses already still cost more upfront. And so we're going to need incentives to get people over the upfront cost, even if their lifetime is comparable in terms of fuel cost. And so this brings me to this headline which you probably saw a few weeks ago, what to know about California's ban on new gasoline-powered cars.

By 2035, California shoppers looking for new vehicles will have to buy electric vehicles. There won't be a ban on the internal combustion engine vehicles that already exist in California. But if you're a shopper buying a new car or a licensing a new vehicle in California, you're probably going to have to license an electric car if it's a new vehicle.

Now, why is this important? What I want to talk about is some of the policies that could be used to basically shape the international auto market, how California has played a key role. And I'd also like to tell the story about Mary Nichols.

Mary Nichols is a 28-year-old Yale Law graduate. She successfully helps to sue the EPA for not enforcing the Clear Air Act in 1970. And this is building on efforts in the State of California to intervene in local air pollution issues that led to the design of air quality management districts and the California Air Resources Board before the US Clean Air Act was passed in 1970.

So from these efforts, both from the State of California, and from these efforts by environmental groups to sue the EPA for not enforcing the Clean Air Act which was passed by Congress in 1970, they essentially pushed California's-- California's regulations for vehicles and air pollution are essentially grandfathered into the Clean Air Act. Mary Nichols joins the California Air Resources Board in 1975, becomes the chairman in 1979. And this is a picture of Mary Nichols more recently in the last decade.

She goes on to work at Bill Clinton's EPA in 1993, works on sulfur dioxide and acid rain. She works on the first national limit for fine particulates, and then rejoined the California Air Resources Board in 2003 under Governor Arnold Schwarzenegger and Governor Jerry Brown. And this is to say that California always had a focus on air pollution before national efforts.

Mary Nichols is-- I just like to use as an example of a young, successful university graduate, like many of you will be, and how she gets involved in air pollution issues, and how California's regulations, which preceded the Clean Air Act, enable California to pass successively more aggressive air pollution legislation or regulations. And so to bring us back to how can you use these standards, the California Air Resources Board standards, or zero emission vehicle mandates. How do you force large national international automakers to conform to your regulations?

Well, California is a large part of the US vehicle market. They decided the goal was going to be 22% of zero emission vehicles in 2025, just a few years from now. And what they do quite effectively is join with other states.

They basically, essentially, form a collision of zero emission vehicle states. This is California plus 13 states, including Massachusetts. That adds about 800,000 vehicles.

Of course, at this-- when the Trump administration try to roll back emission standards that California and these 13 states had basically passed, 23 states actually sued to stop the rollbacks of these EPA standards in the fall of 2019. Even more states sued to stop the rollbacks.

Because once one large state like California has passed certain regulations, automakers want to supply vehicles that state. Once California joined the 13 other states, that's a large fraction of the total auto sales in the United States, which is itself a large auto-consuming country. And 23 states sued to stop these rollbacks in fall of 2019 because states and automakers both liked having some regulatory certainty. And the industry and these states had already agreed on what these zero emission mandates or standards would be.

And one of the aspects of these zero emission standards or mandates from California is that manufacturers have to make enough vehicles. 15.4% of all sales are in California, and so this is essentially getting entities like Volkswagen, or Hyundai, or Kia. If they want to sell vehicles in California, they have to conform to California's standards.

And so some of the analysis that California Air Resources Board does is that this is going to add about $1,900 to the cost of a new vehicle. But this efficiency or these fuel standards will pay for themselves in about three years. We get a 47% reduction in greenhouse gas emissions compared to today, and a 75% reduction in air pollution compared to today.

I think one point worth noticing is that people in California care about greenhouse gas emissions. But these standards or these mandates started with local air pollution and smog. When I was growing up, Los Angeles was known as a quite smoggy place. Air pollution has vastly improved in California, leading to much better health outcomes, and leading to these arguments that not only is it cost efficient, it's also efficient in terms of what we spend on health care or chronic pulmonary heart disease or asthma.

And so California has led to successively more-- has passed successfully more stringent standards and regulations. As I said 2035, the goal is 100% of new vehicles will be sold as zero emission vehicles. There will also be greater use of low-carbon fuels being promoted, such as hydrogen, such as fuel cell vehicles.

By 2050, they'll be trying to phase out all their internal combustion engine cars. So you will be able to drive old gas cars still. So currently, we have almost 100% of all cars in California run on gas.

Their target by 2050 is to have about 53% run on fuel cells, because fuel cells and hydrogen are even more efficient than battery electric vehicles, or prospectively more efficient. Only 17% of cars in 2050 will still be running on battery electric vehicles. 9.7% will be plug-in, and 21% will still be using gasoline. That's their target in 2050.

But what you can see is also a very deliberate, clear regulatory roadmap for automakers to follow. The reason why a lot of automakers want to keep these standards is because they've already developed their technology pathways, or they've already designed their products for the future to meet these standards. They don't want to see these standards fluctuating every four years depending on the occupant of the White House.

And so let's talk a little bit about the Inflation Reduction Act. I just assigned these Hawkins and M. J. Bradley articles to highlight some of the policy design of how the federal government is going to try to incentivize people to buy electric vehicles by getting over the higher upfront cost, even if the future fuel cost is lower. They've extended incentives for manufacturers over 200,000 vehicles. The California Air Resources Board was taking away incentives over 200,000 vehicles, because the idea was that incentives would simply get manufacturers to start building electric vehicles, and they wouldn't need additional incentives.

Of course, three manufacturers passed over the 200,000 vehicle limit, GM, Tesla, and Toyota, and so they no longer got incentives, meaning their cars were no longer cost competitive based on tax incentives, even though the idea is that they start making enough vehicles that they can learn enough and get to enough economies of scale that they compete without tax incentives. One difference in the Inflation Reduction Act is that it gives point of sale tax rebates for EVs to overcome those higher upfront costs. The point of sale tax rebate means that the consumer immediately sees the lower cost of the vehicle, rather than waiting for a tax return credit when they file their taxes.

The Inflation Reduction Act also adds a first-time tax rebate for used electric vehicles, I think $4,000, to create a secondary market for electric vehicles to encourage people to buy electric vehicles, knowing that the subsequent person buying the vehicle from them will be subsidized so that it maintains resale value. Funny thing is, if you look for a used electric vehicle, you'll quite often see electric vehicles that are actually relatively high in price as used vehicles. But because the first owner got a tax incentive, the subsequent owner, even with a low-mileage vehicle, will pay much more than for a new vehicle.

So this first-time tax rebate for used EVs is meant to overcome this problem of the one-time tax rebate for the first owner. And, of course, the part the Hawkins article focuses on the most is that there's new domestic manufacturing requirements for vehicles and batteries, meaning that for the next couple of years. it actually may be relatively hard to buy an electric vehicle because of supply chain issues. But simply, because most electric vehicles aren't manufactured in the US.

The idea is we're going to increase the manufacturing in the US, and we're giving people incentives to manufacture vehicles and batteries in the US. And that's what's going to get incentives going down the road. There's probably more aspects of the Inflation Reduction Act, but I want to focus on the implications for your personal transportation, especially if you're in the market for an electric vehicle in the near future.

So that concludes our lecture today. I'll see you in class for the next lecture. Have a great day.