Physics-aware Data Science:

To Save the Environment and Gas-Money

Presented at:

1. Data Science in Indian County Fifth Geoscience Alliance National Conference, 07.29.2022
2. President's Emerging Scholars program, 08.03.2023, https://emerge.umn.edu/

Roundtable Introduction

- Tell us about yourself!
  - Name, affiliation, interests
  - Anything fun
- Share your thoughts on:
  - Saving fuel
  - Climate change
  - Driving experience

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Eco-routing

Acknowledgement: Tari Jung

Physics-aware Data Science to Save Gas-Money and the Environment

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1. Eco-routing
   a. Why Eco-Routing
   b. Google Maps’ eco-routing
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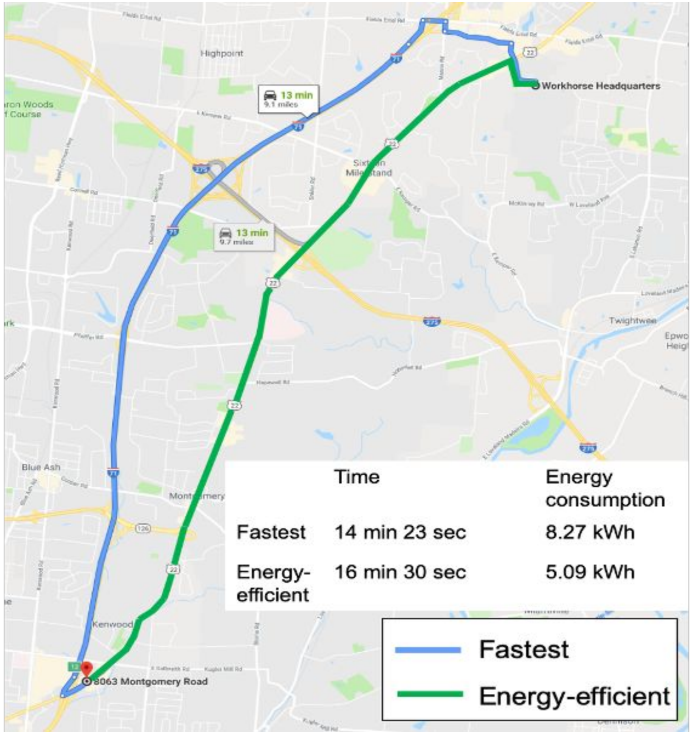


Figure. Energy-efficient vs fastest path
Source: Yan Li, Pratik Kotwal, Pengyue Wang, Yiqun Xie, Shashi Shekhar, and William Northrop. "Physics-guided energy-efficient path selection using on-board diagnostics data." ACM Transactions on Data Science 1, no. 3 (2020): 1-28.

Why Eco-Routing

1. In 2021, 99% of vehicles around the world are driven by combustion engines.

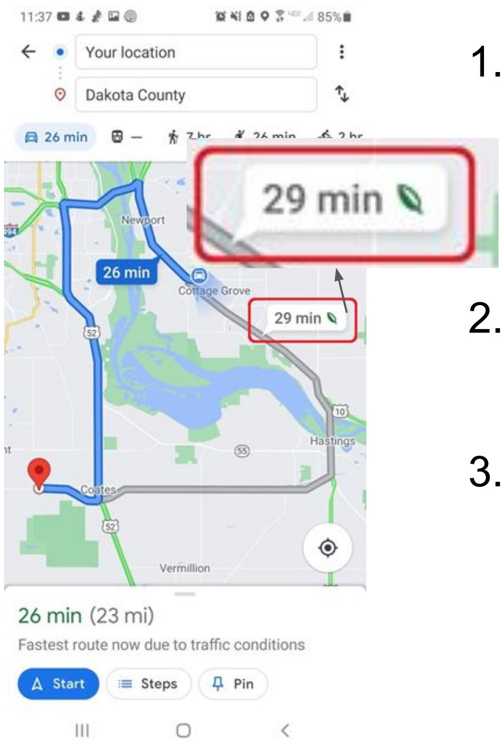
2. This accounts for almost 75% of transportation CO_2 emissions.

3. Only about 4.6% of new passenger vehicles sold in the past few years are electric vehicles (EVs).

4. Google maps estimate finding the most energy-efficient route will help avoid over **one million metric tons of carbon emissions** every year [1]. Reduced emission saves fuel equivalent to removing 200,000 cars from the road per year [2].

CSCI-5715, From GPS, Google Maps, and Uber to Spatial Data Science, Fall 2021, Michael Ung and Alex Pagels, https://view.officeapps.live.com/op/view.aspx?src=http%3A%2F%2Fwww.spatial.cs.umn.edu%2FCourses%2FFall21%2F5715%2Fhomeworks%2FEco_Routing_F2021.pptx&wdOrigin=BROWSELINK
[1] https://www.gstatic.com/gumdrop/sustainability/google-maps-eco-friendly-routing.pdf, via N2021b. Change settings for eco-friendly routing (and How Google Maps calculates fuel-efficiency) , Google Maps, October 2021
[2] 3 new ways to navigate more sustainably with Maps. (n.d.). Retrieved July 25, 2022, from https://blog.google/products/maps/3-new-ways-navigate-more-sustainably-maps/

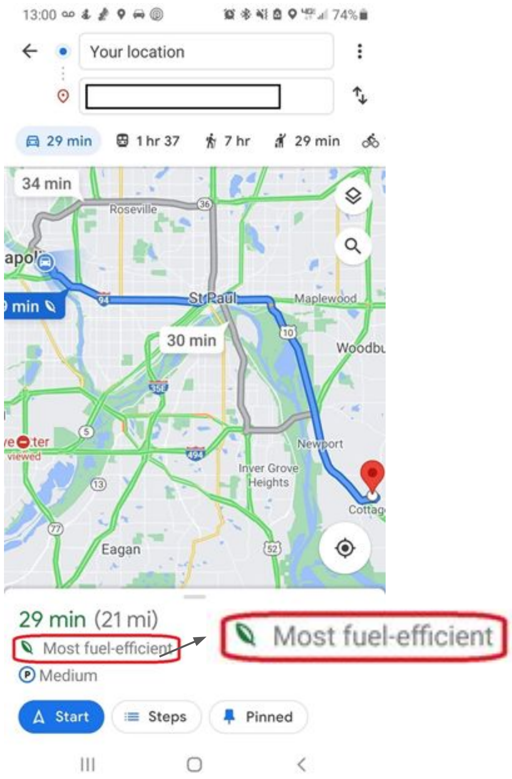
Google Maps' Eco Routing



1. Google launched this option on October 6th, 2021
   a. Might require updating GMap app.

2. Occasionally the route listed will take a few more minutes.

3. Google takes into account some new factors in route calculation[1]:
   a. The steepness of the road
   b. Distance
   c. Predicted speeds
   d. Road type



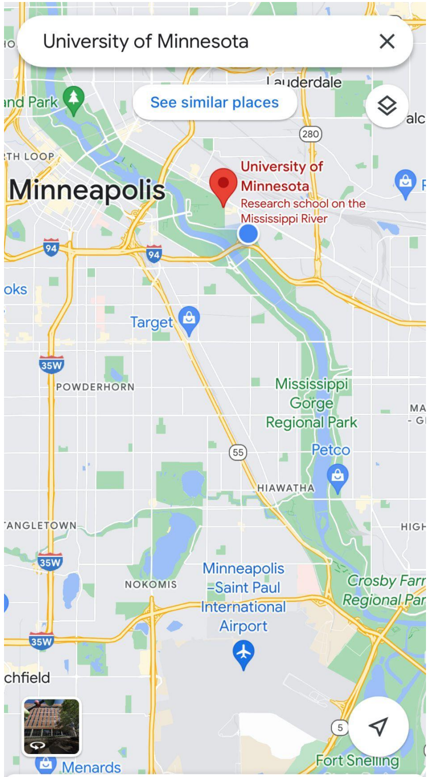
Fastest ✅ Eco Route ❌

Fastest ✅ Eco Route ✅

CSCI-5715, From GPS, Google Maps, and Uber to Spatial Data Science, Fall 2021, Michael Ung and Alex Pagels, https://view.officeapps.live.com/op/view.aspx?src=http%3A%2F%2Fwww.spatial.cs.umn.edu%2FCourses%2FFall21%2F5715%2Fhomeworks%2FEco_Routing_F2021.pptx&wdOrigin=BROWSELINK
[1] https://www.gstatic.com/gumdrop/sustainability/google-maps-eco-friendly-routing.pdf, via
N2021b. Change settings for eco-friendly routing (and How Google Maps calculates fuel-efficiency) , Google Maps, October 2021

Activity: Google Maps' eco-route-selection

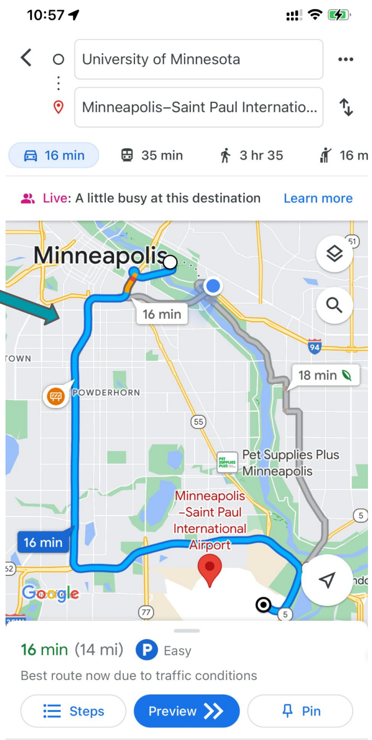
1. Use Google Maps App to find the eco-route between **the University of Minnesota** and the **Minneapolis-Saint Paul International Airport**, then answer questions.
2. Is it the same as the suggested fastest route?
3. If not, draw the fastest route and the eco-route suggested by Google Maps.
4. Try changing time of departure and arrival.
5. Can you try to guess what makes these routes different in travel time and fuel consumption?

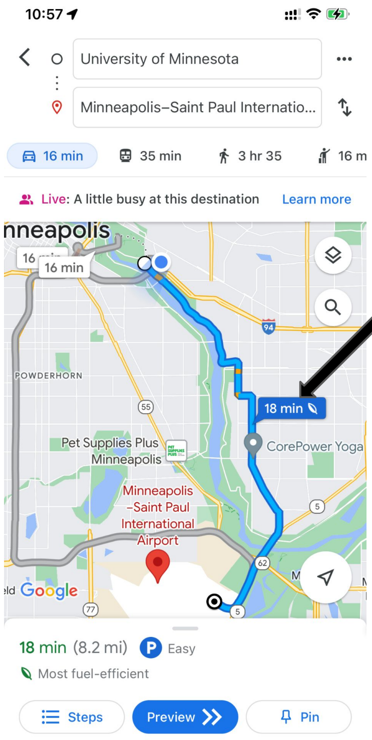


Google Maps' eco-route-selection activity

Have you got the same results?

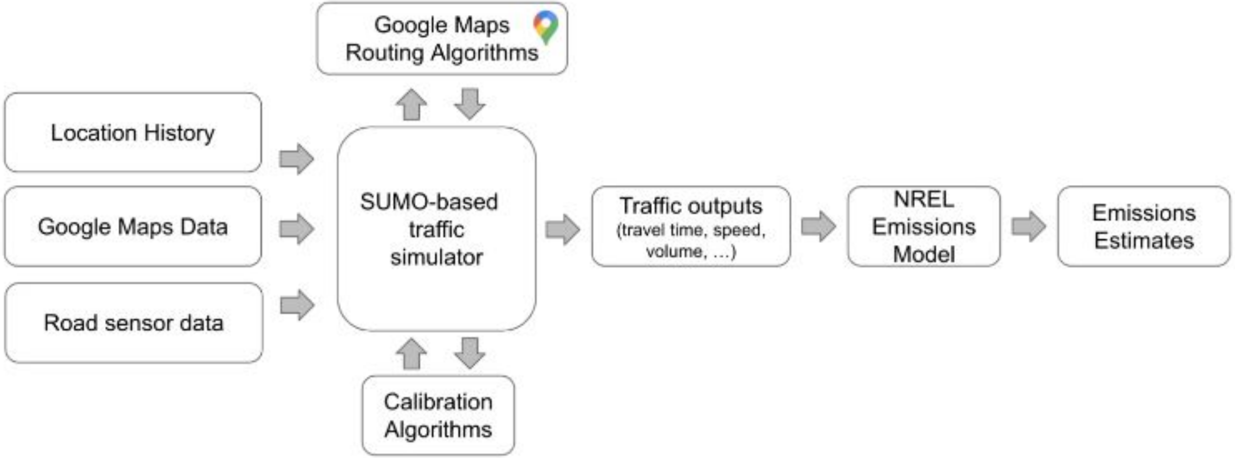
Fastest route:
Long Highway





Eco-route:
Short Urban
Street

How eco-friendly routes are determined



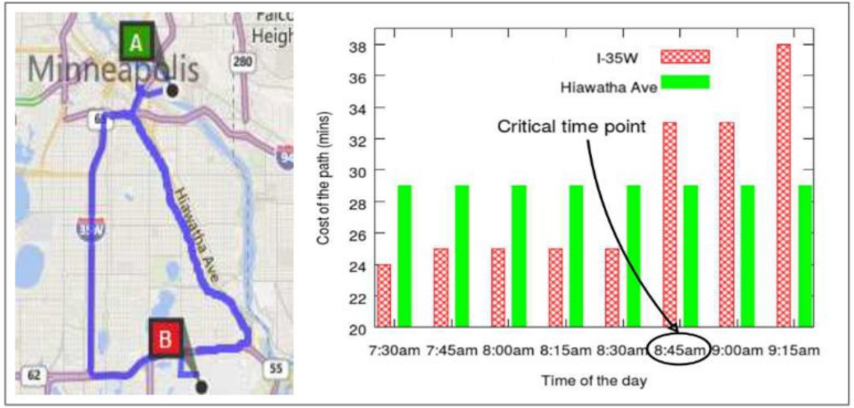
High Level Architecture Diagram of Google Map's Emission Estimation Application

- Analyzes the fuel consumption for all routes driven on Google Maps during the last year using a representative set of vehicle types.
- Using AI and Google Maps' record of available alternative routes at the relevant times, fuel usages of viable alternative routes are calculated.

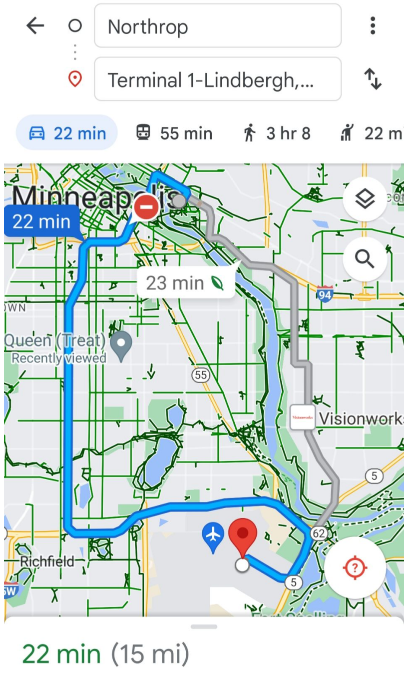
[1] Arora, N., Cabannes, T., Subramaniam, S. G., Li, Y., McAfee, P., Nunkesser, M., Osorio, C., Tomkins, A., & Tsogsuren, I. (2021). *Quantifying the sustainability impact of Google Maps: A case study of Salt Lake City*.

Route vs Energy - Traffic Prediction

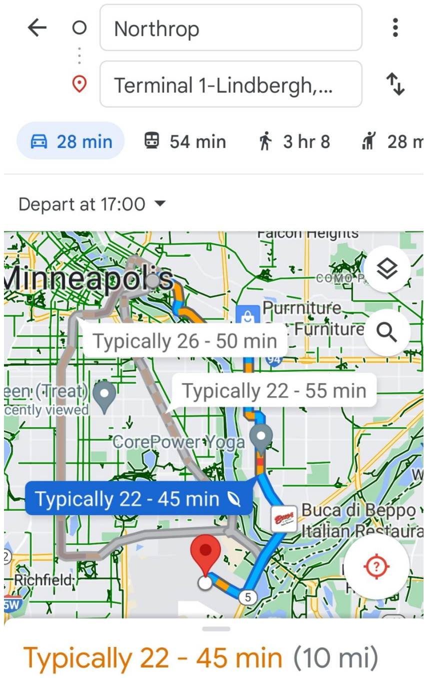
- Google Map compiles travel times for different time of the day and week
- Expected energy consumption of the route is sensitive to the time of departure and arrival



Travel Costs at Different Departure Times



UMN to Airport - Normal Hours

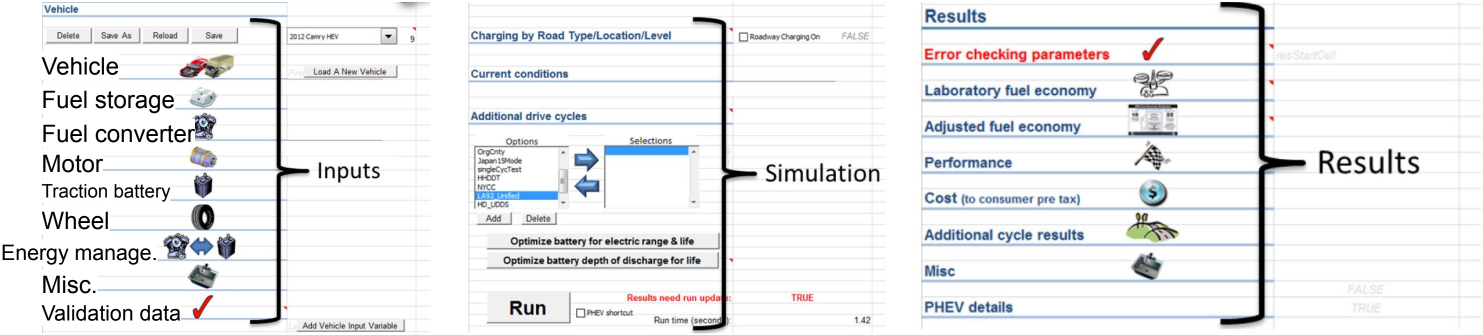


UMN to Airport - Rush Hour

[1] Ali, R. Y., Gunturi, V. M. v., & Shekhar, S. (2015). Spatial big data for eco-routing services. *SIGSPATIAL Special*, *6*(2), 19–25. https://doi.org/10.1145/2744700.2744703

Future Automotive Systems Technology Simulator(FASTSim)

- Fuel consumption prediction generator based on vehicle components and driving conditions
- Accounts for drag, acceleration, ascent, rolling resistance, each powertrain components' efficiency and power limits, and regenerative braking
- Conventional vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, all-electric vehicles, compressed natural gas vehicles, and fuel cell vehicles

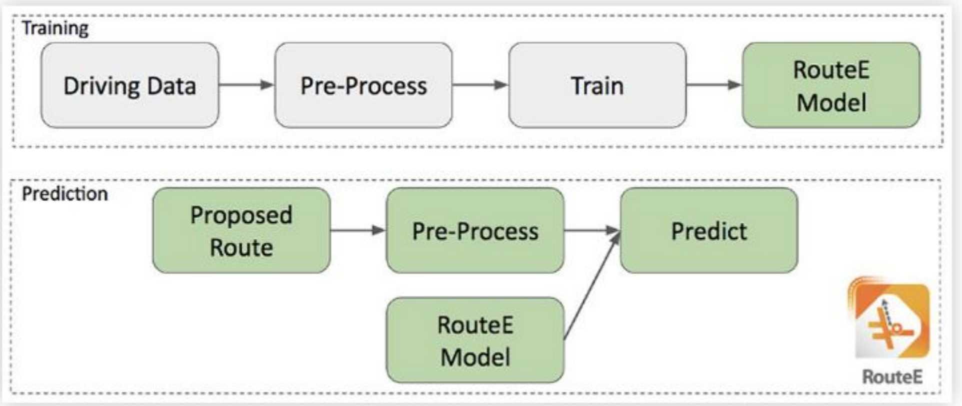


FASTSim Vehicle Parameters

[1] Brooker, A., Gonder, J., Wang, L., Wood, E., Lopp, S., & Ramroth, L. (2015). FASTSim: A Model to Estimate Vehicle Efficiency, Cost and Performance. *SAE Technical Papers*, *2015-April*(April). https://doi.org/10.4271/2015-01-0973

Route Energy Prediction Model (RouteE)

- Estimation of energy consumption for different vehicle types over trips
- FASTSim based individual vehicle emission predictions + 1 million miles of drive cycle data are used for the final estimation of most efficient routes



National Renewable Energy Laboratory.

High Level Architecture Diagram of RouteE

[1] Holden, J., Reinicke, N., & Cappellucci, J. (2020). RouteE: A Vehicle Energy Consumption Prediction Engine. *SAE Technical Papers*, *2020-April*(April). https://doi.org/10.4271/2020-01-0939

Step 1 **FastSim**

Simulate vehicle fuel efficiency across vehicle powertrains

NREL's **FASTSim** technology simulates fuel efficiency across various vehicle types and powertrains, incorporating second-by-second real-world driving data to calculate real-world fuel consumption over different road types and conditions with high accuracy.

Step 2 **RouteE**

Predict fuel consumption across unique routes

NREL's **RouteE** is then trained by the FASTSim-calculated fuel consumption over different driving conditions to predict expected fuel consumption differences among a set of defined routes.

Step 3 **Integrated AI model**

Integrate Google's ML Routing Algorithm

Google integrates the insights and modeling from FASTSim and RouteE across all of Google Maps, incorporating Google's predicted traffic speeds with NREL's fuel consumption modeling to predict fuel consumption for all routes in the U.S., enabling a highly accurate model to maximize fuel efficiency.

Step 4 **Path Selection**

Set parameters to optimize journey time

Finally, we developed a set of parameters and time caps to determine the optimal time vs. fuel usage trade-off within Google Maps to avoid increasing travel time for negligible fuel savings. In this way, the vast majority of our recommended routes continue to be as fast as before.

Google Maps Eco-Friendly Routing Accelerating the journey to sustainability for one billion people (link)

Models go through cycles and improve performances

- Laboratory observations with synthetic constraints become first basis of a model.
- Circumstances occur in real world that are not captured by the initial model.
- Data Science accounts for **real-world scenarios** and **complements laboratory models**.

Source: Parloff, Roger (6 February 2018). "How VW Paid $25 Billion for 'Dieselgate' – and Got Off Easy". Fortune. US. Retrieved 28 August 2018.

Eco-driving

Acknowledgement: Bharat Jayaprakash

Physics-aware Data Science to Save Gas-Money and the Environment

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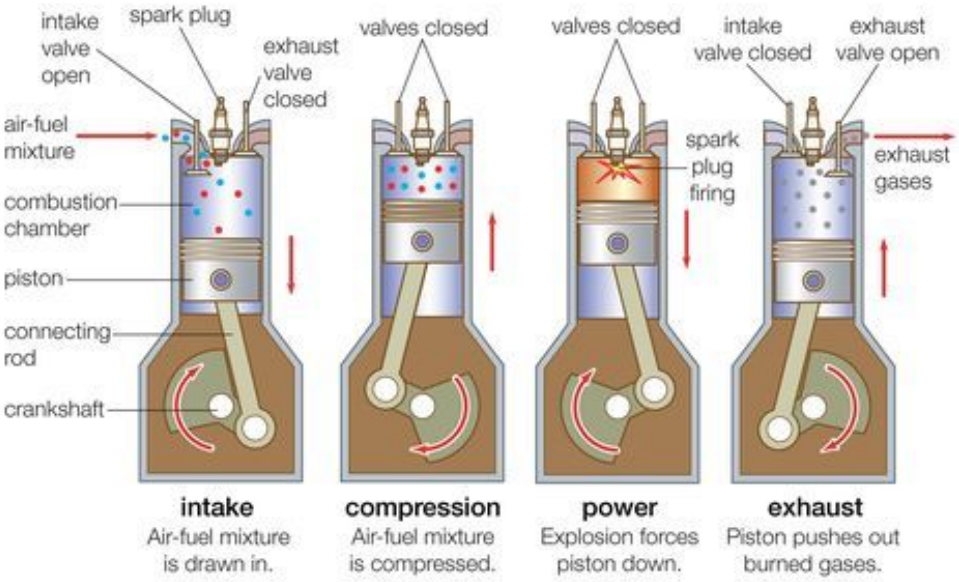
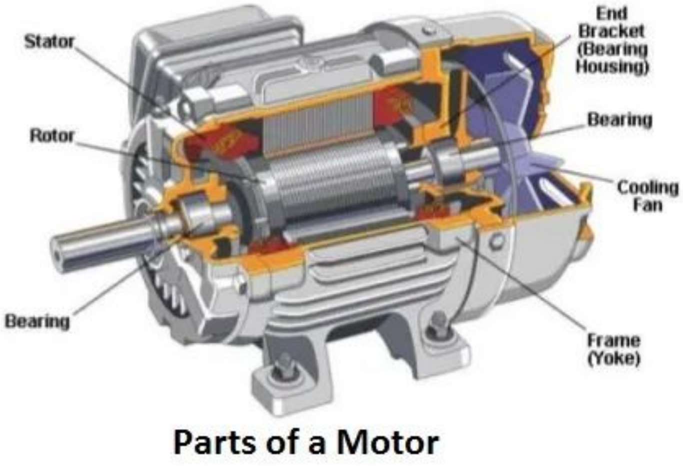
How is the energy produced?



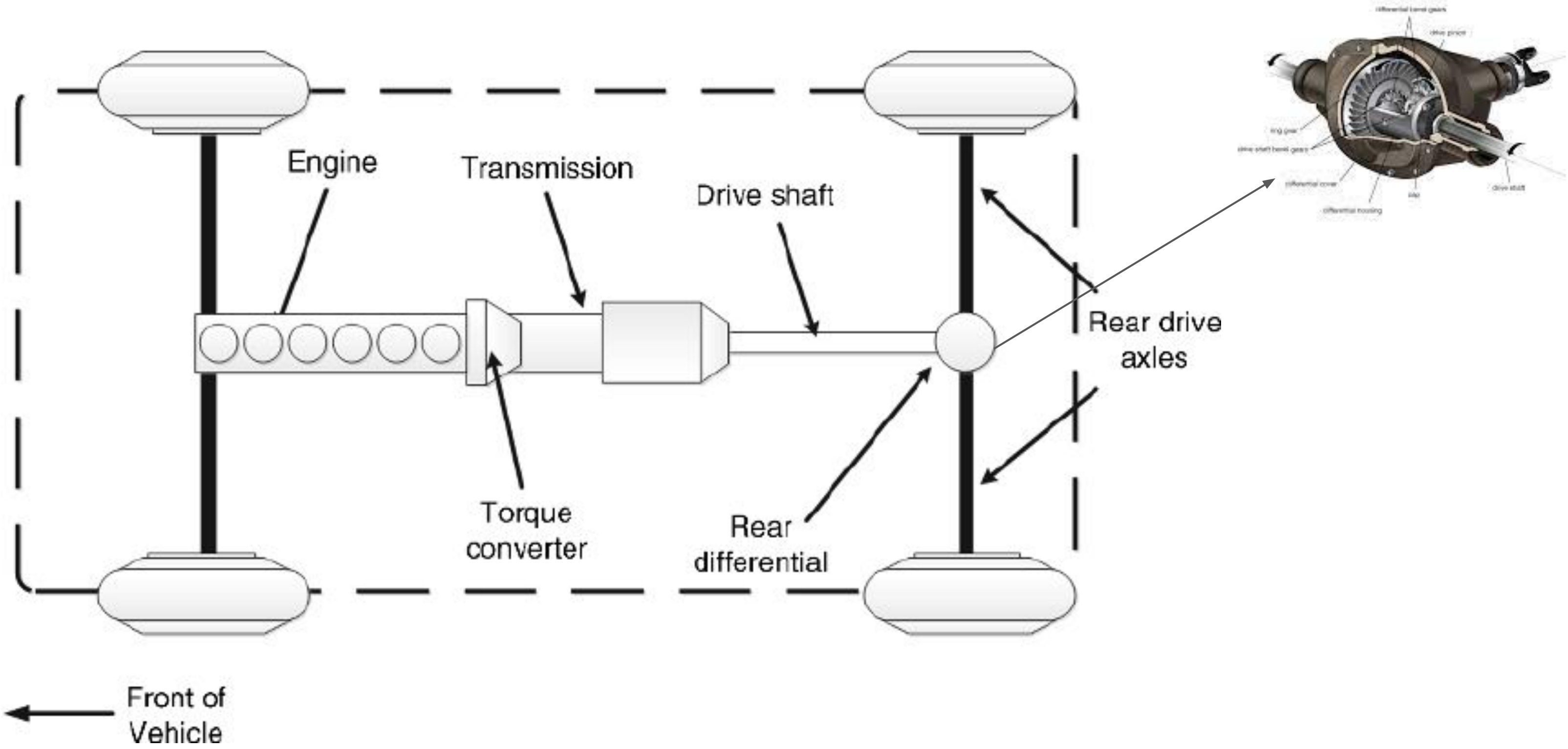


Induction motor

Spark ignition engine

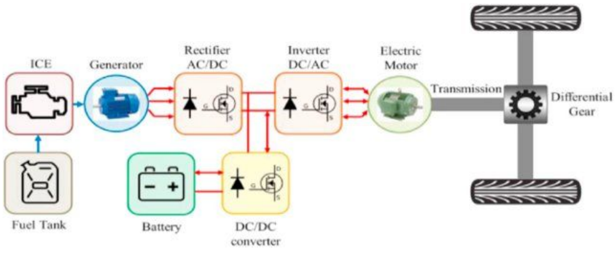
Principle: **Faraday's laws of electromagnetic induction** - relative motion produced by interaction between magnetic field and electric current

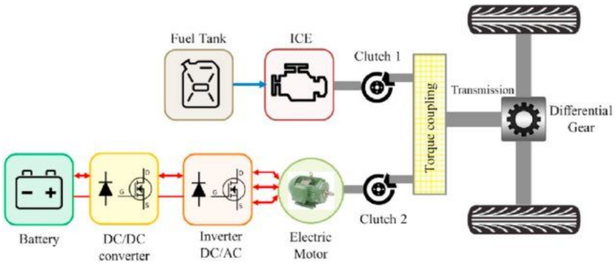
Basic layout of the powertrain

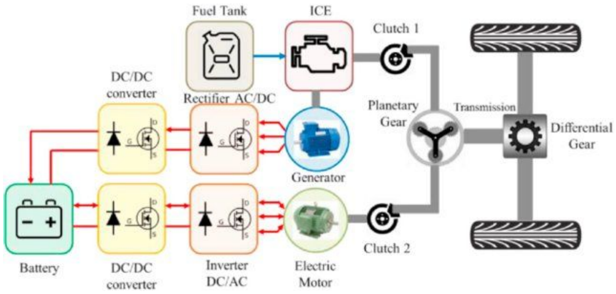


Layout of the powertrain system in a conventional ICE-powered, rear-wheel-drive vehicle

HEV powertrain layouts







Series-HEV

- High performance in stop-and-go driving
- Higher conversion losses at high speeds

Parallel-HEV

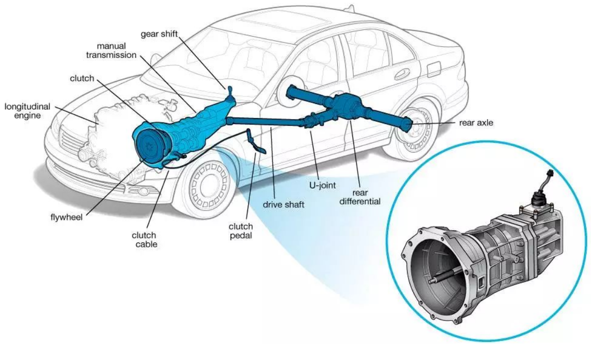
- Less energy losses at high speeds due to coupling
- Less suited for slow urban driving conditions

Series-Parallel-HEV

- Best of both worlds - high performance at lower and higher speeds
- Very expensive system, high control complexity

HEV: Hybrid electric vehicle

The Drivetrain



The drivetrain consists of gears, axles, differential.

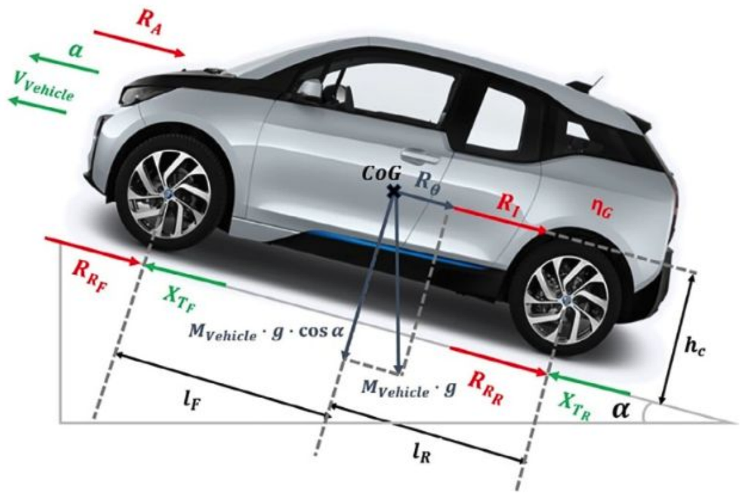
Gear Ratio = (Input speed)/(Output speed)

Gears

$$\text{Force at wheels} = \frac{\text{(Torque generated by engine/motor)x(Gear Ratio)x(Transmission efficiency)}}{\text{Tyre radius}}$$

Power at wheels = Force at wheels x Vehicle Speed

Forces acting on the vehicle



Forces that act on a vehicle:

1. Gradient resistance force R_θ due to road inclination
2. Rolling resistance force R_R due to friction between road and tyre.
3. Aerodynamic drag force R_A due to friction between vehicle and air
4. Inertial resistance force R_I due to the inertia of the vehicle
5. A combination of other forces R_T due to transmission losses

$$R_\theta = M_{\text{Vehicle}} \cdot g \cdot \sin\alpha,$$

$$R_R = C_{RR} \cdot M_{\text{Vehicle}} \cdot g \cdot \cos\alpha,$$

$$\mathrm{R_A} = \frac{1}{2} \cdot \rho \cdot A_F \cdot C_d \cdot (V_{\text{Vehicle}} - V_{\text{wind}})^2$$

$$\mathrm{R_I} = R_{Ia} + R_{I\varepsilon} = \delta \cdot M_{\text{Vehicle}} \cdot a,$$

$$R_T = (R_R + R_A + R_\theta + R_I) \cdot \frac{(1-\eta_G)}{\eta_G}.$$

Power balance and Energy Consumption

Power required at wheels = (Sum of all resistance forces) x Vehicle Speed

Energy consumed = (Sum of all resistance forces x Vehicle displacement) + **OTHER**

For the vehicle to move forward at a particular speed,

Power delivered to the wheels by powertrain = Power required at wheels for particular speed

To reduce energy consumption,

- Minimize force required at wheels
- Minimize **'OTHER'** - idling losses, mechanical losses, heat losses, auxiliary system

Cutting Fuel Costs - changing speed

Change in cruising speed	 Change in mileage - Nissan Altima	 Change in mileage - Toyota RAV4
65 mph → 55 mph	↑ **+ 6 mpg**	↑ **+ 8 mpg**
65 mph → 75 mph	↓ **- 7 mpg**	↓ **- 6 mpg**

Annual savings by driving RAV4 at 55 mph instead of 65 mph = **$354***

*Assumed price of gas is $4.5/gallon. Assumed driving distance is 18,000 highway miles per year.

Cutting Fuel Costs - Additional payload

CR Consumer Reports Payload	 Change in mileage - Nissan Altima	 Change in mileage - Toyota RAV4
Empty roof rack	**- 5 mpg**	**- 2 mpg**
Two mountain bikes on the roof	**- 13 mpg**	**- 7 mpg**
Two mountain bikes on the tail-hitch rack	**- 12 mpg**	**- 5 mpg**

Cutting fuel costs - from the news

Quiz

Which component in the mathematical model of energy consumption estimation is most responsible for the decrease in mileage when additional payload (2 mountain bikes) is attached onto the vehicles?

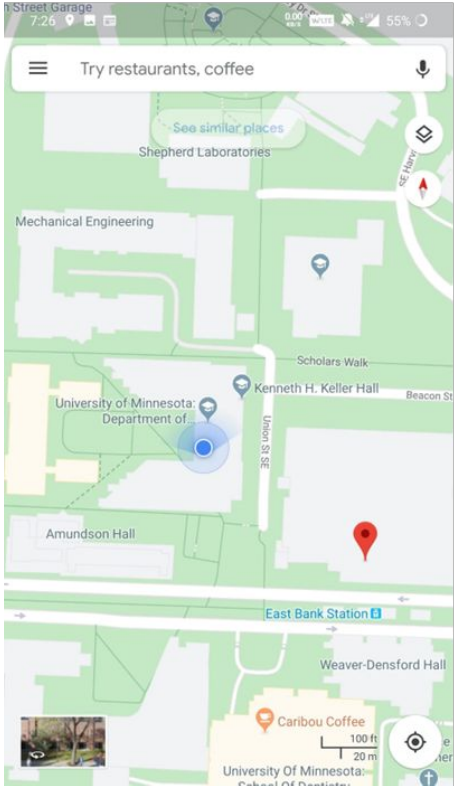
a. Vehicle mass
b. Elevation change
c. Acceleration
d. Rolling friction
e. Wind drag

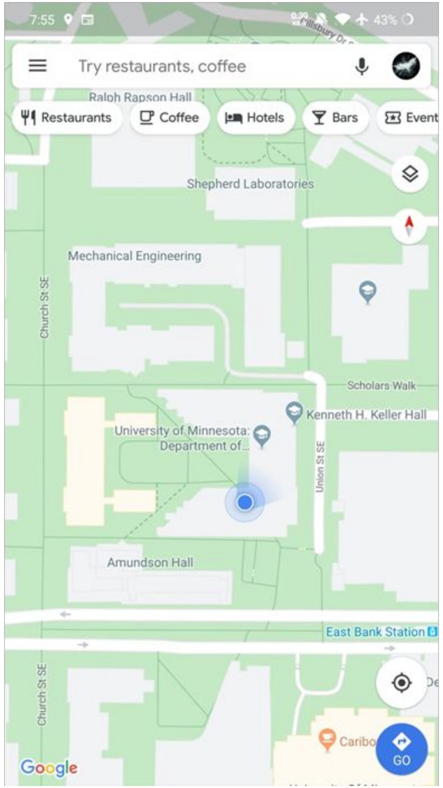
Quiz

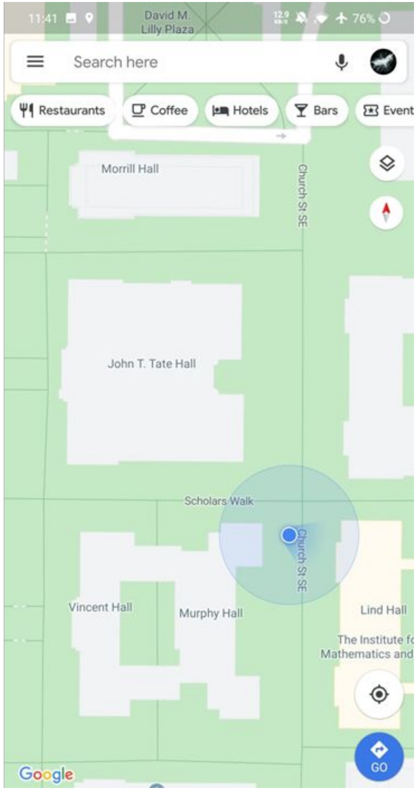
Which component in the mathematical model of energy consumption estimation is most responsible for the decrease in mileage when following the suggestion in the CBS newsclip: “coast downhill”?

a. Vehicle mass
b. Elevation change
c. Acceleration
d. Rolling friction
e. Wind drag

Activities: Positioning Accuracy of WI-FI and GPS







Activities: Positioning Accuracy of WI-FI and GPS

- **EXPERIMENT GOAL**: Compare positioning accuracy of GPS-based and WI-FI based localization methods.
- **EXPERIMENT DESIGN**: Testing locations should include
    - (a) Indoor away from window;
    - (b) Indoor close to window;
    - (c) Outdoor with obstructed view of sky;
    - (d) Outdoor with clear view of sky.
- **PROCEDURE**: In groups of two, find four testing locations observing positioning accuracy of the WIFI and GPS on your smartphone using a mapping app, e.g., Google Maps.
    - **Group member 1** may focus on WIFI-only positioning by turning **ON** airplane mode and then turning **ON** WiFi.
    - **Group member 2** may focus on GPS-only positioning by turning **OFF** airplane mode and turning **OFF** WiFi.

http://www.spatial.cs.umn.edu/Courses/Fall21/5715/index.php?page=lectureNotes/index

Vehicle Big Data

Acknowledgement: By- Mingzhou Yang

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Vehicle Big data: Motivation

- What is the **biggest** worry people tend to have when it comes to electric vehicles (EVs)?

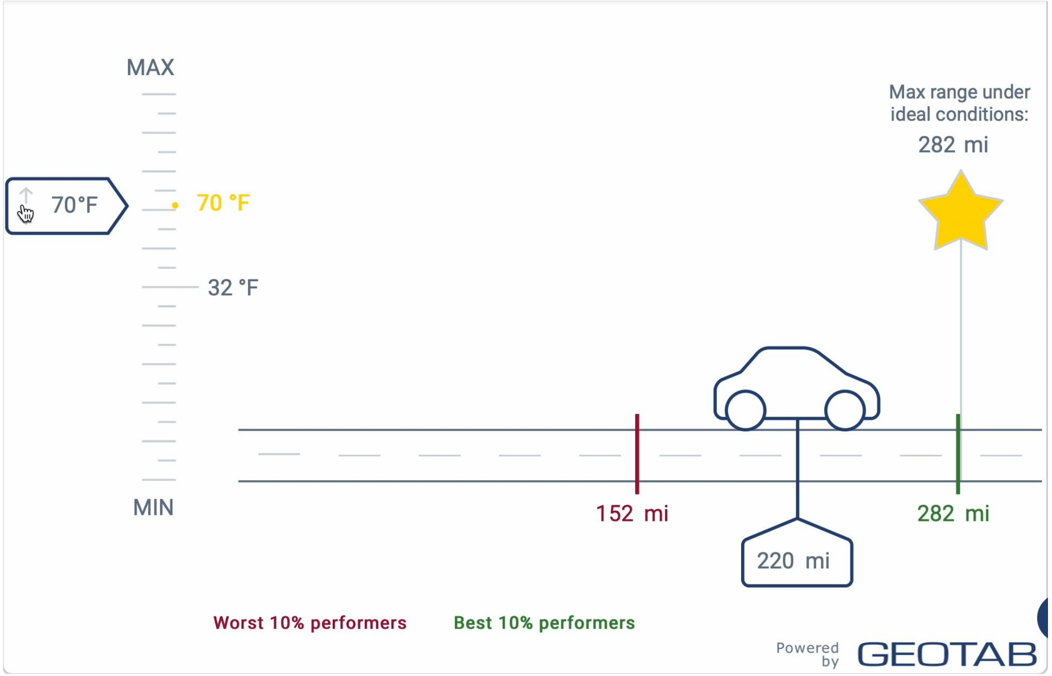
  Range anxiety **The fear of driving an electric vehicle and running out of power, without being able to find a charging station on time to replenish the battery**.

- EV range estimated from laboratory:

  267 mi (Tesla Model 3)

- Estimated by real-world data:

  Changed by temperature:
  - 70°F: 152 mi - 282 mi
  - 98°F: 106 mi - 230 mi
  - **-4°F: 90 mi - 146 mi**



EV range drawn from 4,200 connected EVs and 5.2 million trips. (vehicle model: 2019 Tesla model 3, 54(kWh))
https://www.geotab.com/fleet-management-solutions/ev-temperature-tool/

Vehicle Big data: Motivation

- What makes the laboratory results different from real-world?
    - It is more **complex** in real-world settings.
    - The laboratory experiments using a reference “drive-cycle” **cannot** fully mimic on-road driving conditions.
- For example, drive-cycles used by FASTSim are:
    - 2-cycle testing:
        - **City**: Represents urban driving, in which a vehicle is started with the engine cold and driven in stop-and-go rush hour traffic.
        - **Highway**: Represents a mixture of rural and Interstate highway driving with a warmed-up engine, typical of longer trips in free-flowing traffic.
    - 5-cycle testing: city and highway driving schedules each with the following additional variables:
        - High speeds
        - Air conditioning use
        - Cold temperatures
- *Question*: What conditions are missing?

Brooker, A., Gonder, J., Wang, L., Wood, E. et al., "FASTSim: A Model To Estimate Vehicle Efficiency, Cost, and Performance," SAE Technical Paper 2015-01-0973, 2015, doi:10.4271/2015-01-0973.

Vehicle Big data: Motivation

- What conditions are missing in laboratory ?
  - Weather: snow, rainy
  - Road condition
  - Tires condition
  - …

- *Video*: President Obama’s suggestion to inflate vehicle tires to the proper levels to save (3% – 4%) energy.

https://www.youtube.com/watch?v=akjXqfvLu28

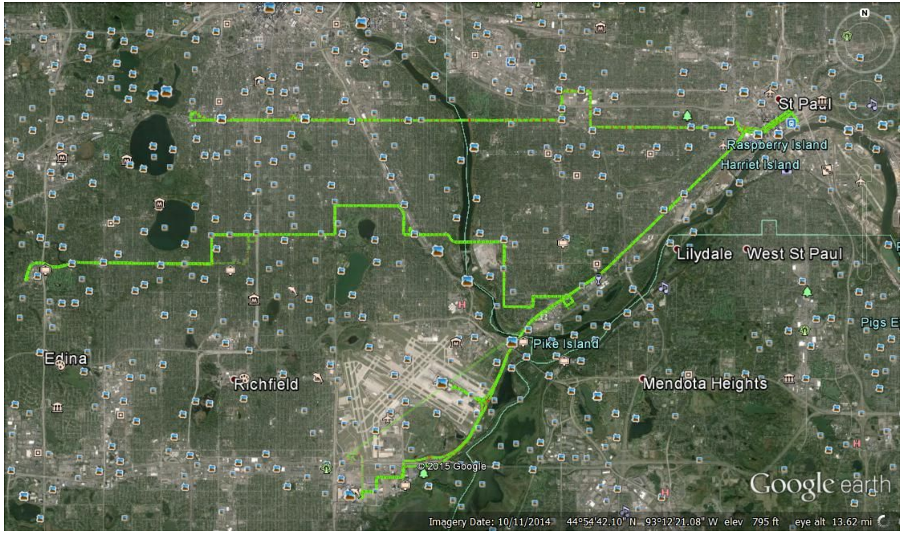
Vehicle Big data: Definition

- Modern vehicles are increasingly being equipped with rich instrumentation to collect **location aware** on-board diagnostics(OBD) data on the **real-world performance** of engines and powertrain.
- **Vehicle measurement big data (VMBD)**, contain a collection of trips on a transportation graph such as a road map [1].
- Each trip is a **time-series** of attributes, such as:
  - vehicle location,
  - fuel consumption,
  - vehicle speed,
  - engine speed in revolutions per minute (RPM),
  - emissions of criteria pollutants like smog-causing nitrogen oxides (NOX)
- High Volume, Velocity, Variety:
  - For connected cars [2]: new cars produce 5GB/hour sensor data
  - 60M cars manufactured each year
  - If driven 4 hours a day: **438 exabytes per year = 0.438 billion terabytes per year**

[1] Reem Y. Ali, Venkata M. V. Gunturi, Shashi Shekhar, Ahmed Eldawy, Mohamed F. Mokbel, Andrew J. Kotz, and William F. Northrop. 2015. Future connected vehicles: challenges and opportunities for spatio-temporal computing. In Proceedings of the 23rd SIGSPATIAL International Conference on Advances in Geographic Information Systems (SIGSPATIAL '15). Association for Computing Machinery, New York, NY, USA, Article 14, 1–4.
[2] J. I. Speed. Iot for v2v and the connected car. http://goo.gl/3b5NSy, 2014.

Vehicle Big data: An example

- A sample engine measurement dataset collected from an on-board sensor on a diesel Metro Transit bus in Twin Cities, MN.
- The dataset measured 133 engine and environmental variables at a rate of 1 Hz.
- The data covered roughly 19 days in winter 2014 (≈ 176 trips) on three different routes, ensuring the data was not biased by a specific route.



Visualization of the trajectories of the Metro Transit bus data

Kotz, Andrew J; Northrop, William F. (2019). Metro Transit Diesel Bus Engine Measurement Data for 19 Days in Winter 2014 in Minneapolis-St. Paul, MN, USA. Retrieved from the Data Repository for the University of Minnesota, https://doi.org/10.13020/tfje-5p82.

Vehicle Big data:Connection with eco-routing

- To do eco-routing: energy estimation is important.
  - Inaccurate estimation can lead to energy-inefficient results.

- Geo-referenced vehicle big data facilitate **accurate** travel cost estimation (even on unseen path) and novel eco-routing algorithms using the estimation.

- Features used in current energy estimation methods:
  - Mass
  - Speed limit
  - Elevation change
  - Previous orientation: turning angle from the previous segment
  - Length
  - Direction angle
  - Road type
  - Starting times of the day, and the day of the week
  - Lanes
  - Bridge
  - Endpoints type: traffic signal/ crossing/ motorway junction …

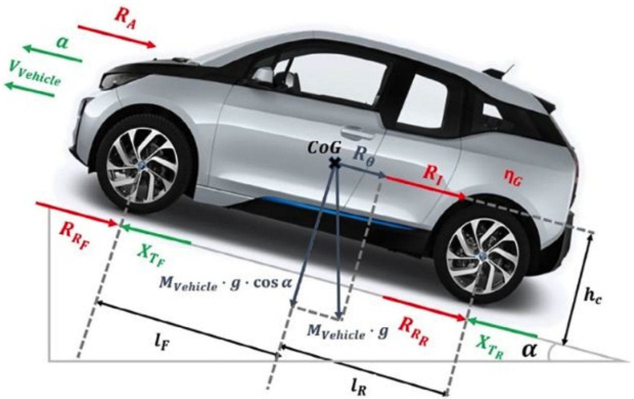
Vehicle Big data: Activities

- Explore the spreadsheet listing the each variable in the Metro Transit bus dataset and its description.
- A review of the **energy consumption equations** is also attached.

- In groups of two, explore the spreadsheet and answer the following questions:
    - Which attributes are in the equations?
    - Which attributes can be relevant to the energy consumption but are not in the equations?
    - What attributes in the equations are not captured in the spreadsheet?

- Link to online versions of the document:
  Data description (simplified), Data description (full version)

Physics-aware



Forces that act on a vehicle:

1. Gradient resistance force R_θ
2. Rolling resistance force R_R
3. Aerodynamic drag force R_A
4. Inertial resistance force R_I
5. A combination of other forces R_T

Power required at wheels = (Sum of forces) x Vehicle Speed

$$W = \int \left(\frac{1}{2\eta} c_{air} A \rho v^3\right) dt + \int \left(\frac{m}{\eta} a v\right) dt + \int \left(\frac{m}{\eta} c_{rr} g v\right) dt + \int \left(\frac{m}{\eta} g v_h\right) dt$$

Data Science: Description of the Metro Transit data (simplified)

Name	Description
Year	Year
Month	Month
Day	Day of the month
Hour	hour (0-23)
Min	minute (0-59)
Sec	second (0-59)
Latitude	Latitude
Longitude	Longitude
GPSspeed	GPS speed in Miles per hour
Elevation	elevation in meters
ambT	ambient temperature measured from bus in celsius
Acpwr	air conditioning power (kw)
Totallbs	total weight lbs

Thank you!