



*TSITE 2015 Summer Meeting
The Park Vista Hotel, Gatlinburg, TN*

Customizing Driving Cycles for Fuel Economy Estimation

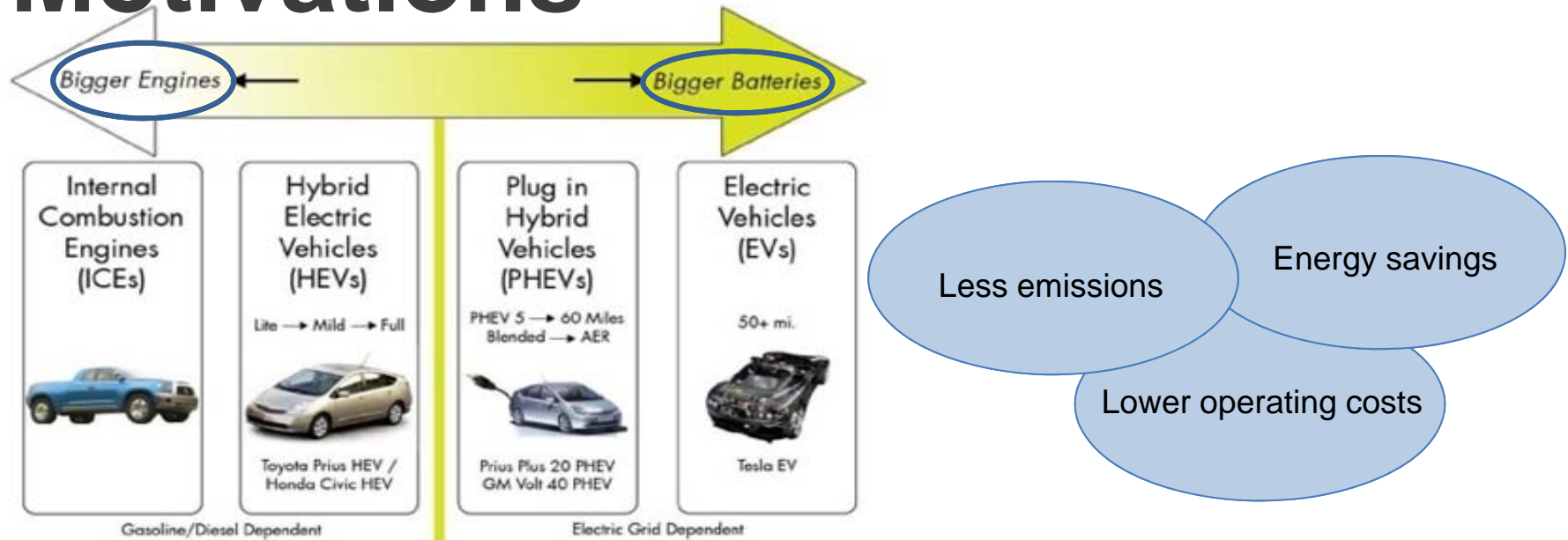
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THE UNIVERSITY OF
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Motivations



Sources:

<http://phev.ucdavis.edu/about/faq-phev/>

<http://www.c2es.org/blog/nigrn/making-case-plug-electric-vehicles-smart-shopping>

BAD GOP, BAD GOP. PHOTOGRAPHER: DREW ANGER/GETTY IMAGES



CARS Automakers Get Caught Not Breaking EPA Rules

NOV 6, 2014 2:04 PM EST
By Edward Niedermeyer

U.S. Attorney General Eric Holder rained magisterial judgment this week on Hyundai Motor Co. and Kia Motors Corp., which the U.S. claimed had overstated their cars' fuel economy on the vehicles' window stickers. He said the government's \$350 million settlement with the South Korean automakers "will send an important message

This might be a reasonable strategy if the EPA's standards consistently delivered MPG ratings that reflect real-world driving, but the ratings simply don't do that. Consumer Reports has shown that 55 percent of hybrid vehicles **fall short of their EPA ratings** by 10 percent or more in independent testing, while 28 percent of cars with turbocharged engines have the same problem. The EPA itself acknowledged this shortcoming earlier this year, when it **proposed "in-use auditing"** -- testing vehicles on the road -- to verify window-sticker numbers as part of **its broader effort** to bring its test results closer in line with real-world efficiency.

Fuel-economy ratings are a tool for consumers, and the fact that the EPA acknowledges that its tests fail to reflect the numbers consumers are likely to see on window stickers is the real scandal. Rather than shaming Hyundai and Kia for exploiting "latitude" in their testing standards, the EPA should work to eliminate that latitude as part of a wider effort to make its ratings reflect real-world use. In addition to tightening test-condition standards, the EPA should consider verifying a higher percentage of tests, creating a strong in-use

These Tests Failed You: Why Is the EPA So Bad at Estimating Hybrid Fuel Economy?

The fuel-economy numbers look nice, but the testing behind them is flawed.

MAY 2013 | BY CSABA CSERE | MULTIPLE PHOTOGRAPHERS

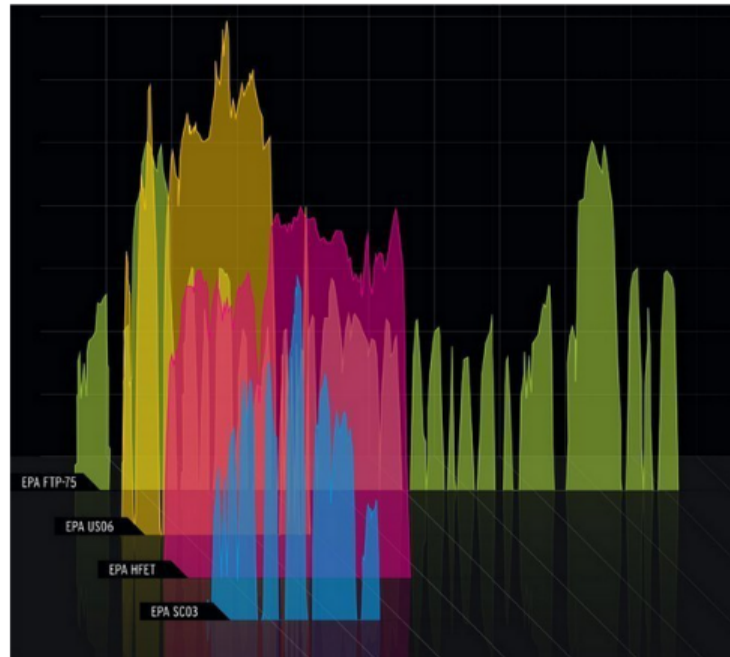
141 SHARES

35 TWEETS

g+

✉

💬



From the April 2013 issue of *Car and Driver*
We were impressed when Ford announced that the 2013 Fusion hybrid earned an EPA rating of 47 mpg for both city and highway driving. Here was a generously sized and relatively conventional-looking sedan rivaling the efficiency of the Toyota Prius.

Then we racked up a mere 32 mpg in our road test (December 2012). That's par for our foot-down driving style, but even when we drove more sedately, we had difficulty coaxing the Fusion's trip computer to show any number that started with a 4. It turns out we weren't alone.

In early December, a California law firm filed a class-action suit against Ford, charging fraud and "widespread misleading and

Motivations

Based on pre-designed and fixed driving cycles
In laboratory conditions

EPA Fuel Economy Estimates
These estimates reflect new EPA methods beginning with 2008 models.

| | | |
|---|--|---|
| CITY MPG 18 <small>Expected range for most drivers 15 to 21 MPG</small> | Estimated Annual Fuel Cost \$2,039 <small>based on 15,000 miles at \$2.80 per gallon</small> | HIGHWAY MPG 25 <small>Expected range for most drivers 21 to 29 MPG</small> |
| Combined Fuel Economy This Vehicle 21 <small>10 — 31 All SUVs</small> | | |

Your actual mileage will vary depending on how you drive and maintain your vehicle.

See the FREE Fuel Economy Guide at dealers or www.fueleconomy.gov



Driving cycles different by car, driver, local conditions...
In Real-world driving

EPA Fuel Economy Estimates
These estimates reflect new EPA methods beginning with 2008 models.

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| Combined Fuel Economy This Vehicle 21 <small>10 — 31 All SUVs</small> | | |

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“One size-fits-all” MPG rating



Need convincing fuel economy predictions based on:

- drivers' characteristics &
- contemporary real-world driving

EPA Driving Cycles

| Drive Cycle | Description | Data Collection Method | Year of Data | Top Speed | Avg. Speed | Max. Acc. | Distance | Time (min) | Idling time |
|-------------|-------------------------------|--|--------------|-----------|------------|-----------------------|-----------|------------|-------------|
| FTP | Urban/City | Instrumented Vehicles/Specific route | 1969 | 56 mph | 20 mph | 1.48 m/s ² | 17 miles | 31 min | 18% |
| C-FTP | city, cold ambient temp | Instrumented Vehicles/ Specific route | 1969 | 56 mph | 32 mph | 1.48 m/s ² | 18 miles | 31min | 18% |
| HWFET | Free-flow traffic on highway | Specific route Chase-car/ naturalistic driving | Early 1970s | 60 mph | 48 mph | 1.43 m/s ² | 16 miles | 12.5 min | None |
| US06 | Aggressive driving on highway | Instrumented Vehicles/ naturalistic driving | 1992 | 80 mph | 48 mph | 3.78 m/s ² | 13 miles | 10min | 7% |
| SC03 | AC on, hot ambient temp | Instrumented Vehicles/ naturalistic driving | 1992 | 54 mph | 35 mph | 2.28 m/s ² | 5.8 miles | 9.9 min | 19% |

Research Question

- How to design customized driving cycles to capture real-world driving?
 - Different fuel types: Gasoline, EV, Hybrid ...
 - Different vehicle body types: Sedan, SUV, Pick-up...
 - Different trips: short/long trip...
 - Different driver attributes: Male/Female, Age...
 - Different driving styles: Calm driving, jerky driving...

Sounds impossible?



Unless we have the data!

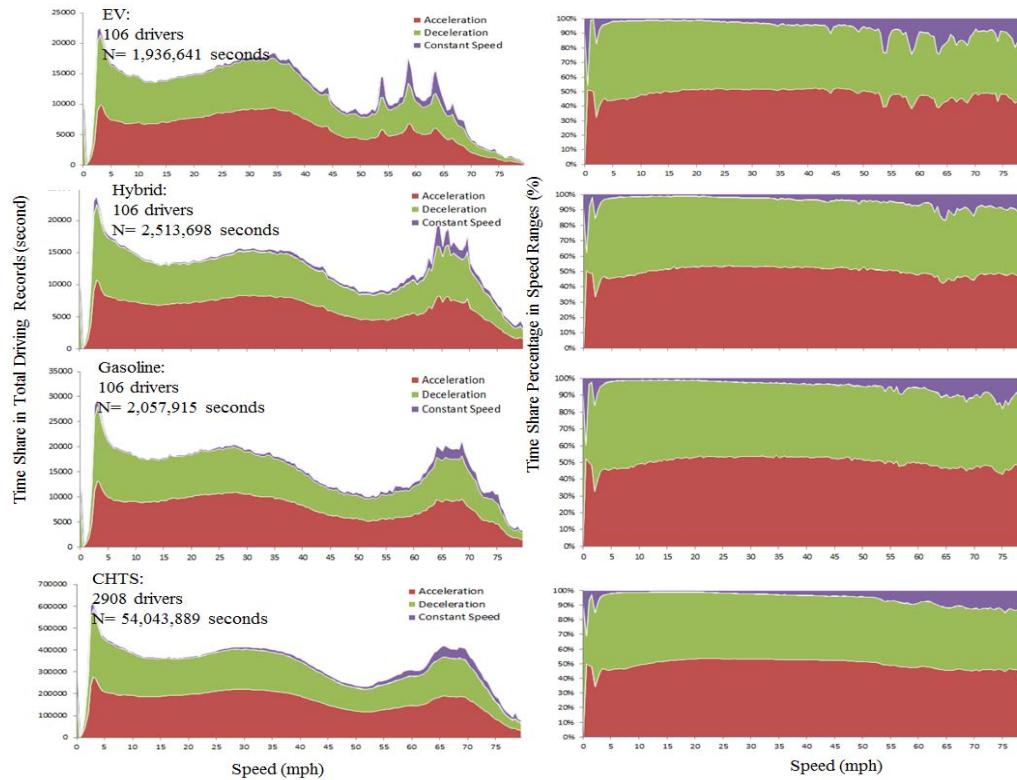
- Large-scale driving data now available
 - California Household Travel Survey (CHTS)
 - Jan 2012-Jan 2013
 - Data collected by in-vehicle GPS or OBD & survey
- **54 million** seconds of vehicle trajectories
 - More than 65,000 trips
 - Made by 3,000 drivers
 - 2,200 GV, 364 HV, 109 EV, 110 Diesel



“Equivalent” Groups

| Vehicle Group | Demographics | Mean | Std. Dev. | Min | Max | |
|-------------------------|---------------------|-------------------|-----------|-------|-----|---|
| EV (N=106) | Age (years) | 49.415 | 10.403 | 16 | 71 | |
| | Gender [Male] | 0.575 | 0.497 | 0 | 1 | |
| | Household Income | < 74,999 | 0.038 | 0.191 | 0 | 1 |
| | | 75,000 - 99,999 | 0.123 | 0.330 | 0 | 1 |
| | | 100,000 - 149,000 | 0.264 | 0.443 | 0 | 1 |
| >150,000 | | 0.575 | 0.497 | 0 | 1 | |
| Hybrid (N=106) | Age (years) | 49.394 | 9.767 | 20 | 68 | |
| | Gender [Male] | 0.575 | 0.497 | 0 | 1 | |
| | Household Income | < 74,999 | 0.038 | 0.191 | 0 | 1 |
| | | 75,000 - 99,999 | 0.123 | 0.330 | 0 | 1 |
| | | 100,000 - 149,000 | 0.264 | 0.443 | 0 | 1 |
| >150,000 | | 0.575 | 0.497 | 0 | 1 | |
| Gasoline (N=106) | Age (years) | 49.415 | 10.403 | 16 | 71 | |
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| | Household Income | < 74,999 | 0.038 | 0.191 | 0 | 1 |
| | | 75,000 - 99,999 | 0.123 | 0.330 | 0 | 1 |
| | | 100,000 - 149,000 | 0.264 | 0.443 | 0 | 1 |
| >150,000 | | 0.575 | 0.497 | 0 | 1 | |
| All drivers (N=2908) | Age (years) | 48.804 | 13.490 | 16 | 88 | |
| | Gender [Male] | 0.480 | 0.500 | 0 | 1 | |
| | Household income | < 74,999 | 0.312 | 0.216 | 0 | 1 |
| | | 75,000 - 99,999 | 0.187 | 0.390 | 0 | 1 |
| | | 100,000 - 149,000 | 0.232 | 0.422 | 0 | 1 |
| >150,000 | | 0.269 | 0.443 | 0 | 1 | |

Comparing acceleration-speed & time use



Time spent on accelerating or braking varies with speeds

PEVs spent less time >60 mph

Distinct spikes in EV time use distribution

Comparison of driving performance-trip level

| Vehicle-Trip Groups | EV (N=2371) | | HV (N=2652) | | GV (N=2397) | | Regional (all trips) (N=65,652) | | Existing Drive Cycles | | | | | | |
|--|-------------|-------|-------------|-------|-------------|-------|------------------------------------|-------|-----------------------|--------|-------|-------|-------|-------|--|
| | Mean | S.D. | Mean | S.D. | Mean | S.D. | Mean | S.D. | FTP | HWY | US06 | SC03 | LA92 | NYCC | |
| Drive Cycle Parameters | | | | | | | | | | | | | | | |
| Total duration (hrs) | 0.26 | 0.23 | 0.30 | 0.30 | 0.27 | 0.31 | 0.26 | 0.30 | 0.17 | 0.40 | 0.52 | 0.21 | 0.17 | 0.17 | |
| Driving duration (hrs) | 0.22 | 0.21 | 0.26 | 0.27 | 0.24 | 0.29 | 0.23 | 0.28 | 0.15 | 0.33 | 0.42 | 0.21 | 0.13 | 0.11 | |
| Total average speed (mph) | 26.89 | 10.91 | 28.07 | 12.61 | 27.80 | 12.16 | 27.28 | 12.37 | 47.97 | 24.61 | 21.20 | 48.20 | 21.44 | 7.09 | |
| Driving average speed (mph) | 27.22 | 10.89 | 28.38 | 12.59 | 28.14 | 12.13 | 27.62 | 12.35 | 51.85 | 29.40 | 26.20 | 48.58 | 26.62 | 10.92 | |
| Maximum speed (mph) | 49.30 | 15.83 | 51.96 | 17.83 | 51.45 | 17.11 | 50.22 | 17.43 | 80.30 | 67.20 | 56.70 | 59.90 | 54.80 | 27.70 | |
| Average acceleration (ft/s ²) | 2.13 | 0.68 | 2.07 | 0.65 | 2.22 | 0.71 | 1.46 | 0.47 | 2.20 | 2.21 | 1.68 | 0.64 | 1.65 | 2.04 | |
| Average deceleration (ft/s ²) | -2.19 | 0.64 | -2.24 | 0.68 | -2.38 | 0.76 | -1.58 | 0.50 | -2.39 | -2.47 | -1.89 | -0.72 | -1.98 | -1.99 | |
| Maximum acceleration (ft/s ²) | 9.34 | 2.24 | 8.84 | 1.84 | 8.82 | 1.92 | 5.91 | 1.31 | 12.32 | 10.12 | 4.84 | 4.69 | 7.48 | 8.80 | |
| Maximum deceleration (ft/s ²) | -9.94 | 2.36 | -10.25 | 2.47 | -10.37 | 2.47 | -6.91 | 1.70 | -10.12 | -12.91 | -4.84 | -4.84 | -8.95 | -8.65 | |
| Root mean square acceleration (ft/s ²) | 1.47 | 0.43 | 1.46 | 0.44 | 1.56 | 0.48 | 1.03 | 0.32 | 3.24 | 2.61 | 2.07 | 0.98 | 2.26 | 2.21 | |
| Average positive vehicular jerk (ft/s ³) | 0.77 | 0.29 | 0.77 | 0.30 | 0.80 | 0.30 | 0.54 | 0.21 | 1.32 | 1.25 | 0.78 | 0.28 | 1.02 | 1.41 | |
| Average negative vehicular jerk (ft/s ³) | -0.60 | 0.20 | -0.60 | 0.20 | -0.63 | 0.20 | -0.42 | 0.14 | -1.22 | -1.19 | -0.66 | -0.27 | -0.80 | -1.28 | |
| Maximum positive vehicular jerk (ft/s ³) | 6.48 | 2.08 | 6.35 | 2.05 | 6.40 | 2.19 | 4.25 | 1.51 | 11.15 | 9.53 | 5.13 | 2.93 | 6.31 | 8.21 | |
| Maximum negative vehicular jerk (ft/s ³) | -2.94 | 0.81 | -2.92 | 0.72 | -2.94 | 0.76 | -1.97 | 0.52 | -8.65 | -12.32 | -3.81 | -2.35 | -4.11 | -6.16 | |
| Root mean square jerk (ft/s ³) | 0.69 | 0.18 | 0.69 | 0.19 | 0.71 | 0.19 | 0.47 | 0.13 | 1.82 | 1.52 | 0.93 | 0.37 | 1.18 | 1.50 | |
| Acce./dece. events (no. per mile) | 16.90 | 14.39 | 16.86 | 14.55 | 16.84 | 15.33 | 17.62 | 17.12 | 16.73 | 10.90 | 9.56 | 2.24 | 15.64 | 39.44 | |
| % time on idling | 20.64 | 13.06 | 20.00 | 13.02 | 21.03 | 13.46 | 20.85 | 13.93 | 11.15 | 24.58 | 23.84 | 1.57 | 24.46 | 51.75 | |
| % time on acceleration | 37.89 | 6.82 | 39.50 | 6.84 | 38.97 | 7.21 | 39.10 | 7.33 | 44.09 | 34.96 | 37.28 | 43.86 | 40.27 | 24.87 | |
| % time on deceleration | 40.71 | 9.27 | 39.75 | 8.64 | 39.25 | 8.85 | 39.26 | 9.21 | 39.27 | 28.76 | 31.47 | 38.12 | 31.45 | 21.87 | |
| % time on stable driving | 5.60 | 7.85 | 4.76 | 6.16 | 4.41 | 6.16 | 4.57 | 6.34 | 5.49 | 7.38 | 3.52 | 16.45 | 2.16 | 0.00 | |
| % time on outlier accel./decel. | 4.46 | 3.75 | 4.69 | 3.96 | 5.59 | 4.77 | 5.15 | 4.52 | | | | | | | |
| % time on outlier vehicular jerk | 4.79 | 4.11 | 4.80 | 3.91 | 5.32 | 4.30 | 5.00 | 4.18 | | | | | | | |
| Kinetic Intensity | 3.29 | 8.53 | 3.35 | 5.50 | 3.30 | 5.36 | 3.68 | 22.88 | | | | | | | |

Findings based on comparison

- Trips in EVs are shorter in terms of driving duration
- EVs have lower average speed/driving speed
- Average maximum trip speed of EV trips is near 50 mph (lower than similar HV and GV, and substantially lower than four EPA standard driving cycles and LA92)
- Average vehicle jerk level is similar for EV, HV and GV (close to US06, significantly higher than other EPA driving cycles)
- Existing driving cycles do not represent AFV driving very well

Customizing driving cycles

- Break trip into components (micro-trips)
- Micro-trip → Base element for driving cycle design
 - Starts and ends at zero speed
- Trip consists of micro-trips chained together
- It is critical to have:
 - Sufficiently large collection of historical cases
 - Mechanism for chaining together micro-trips

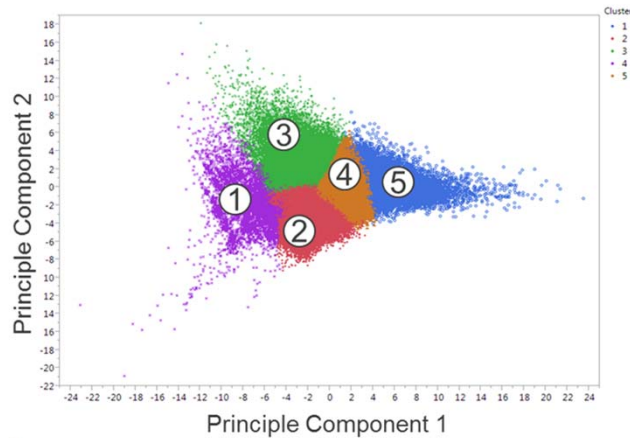
Solution:

Case Based System for Driving Cycle Design (CBD CD)

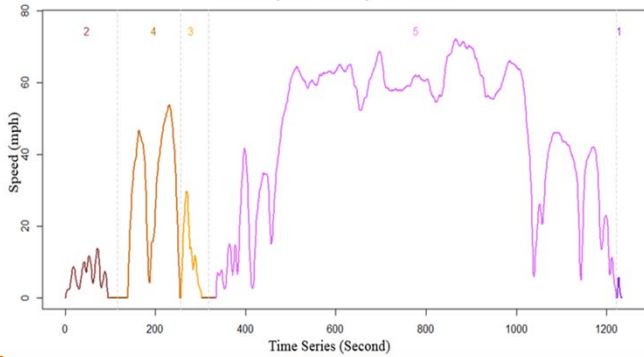
What is CBDCCD?

- A computer-based machine learning tool
 - Retain richness of **historical** micro-trip cases
 - Synthesize **new** candidate driving cycles that are closest to the user
- CBDCCD is able to:
 - Apply clustering based on 23 performance parameters to develop the micro-trip collection
 - Match, rank, & synthesize micro-trip cases into sequence which forms customized driving cycle

Database preparation (Clustering and PCA)

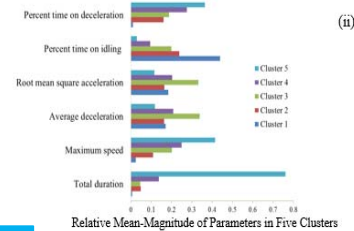
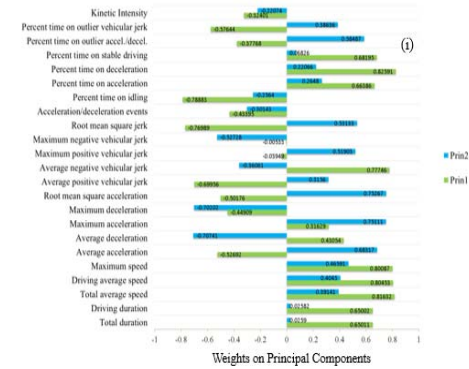


Group these micro-trips based on the various driving parameters extracted



Trip: code sequence 24351

Micro-trip cluster identified (sample trip)



Driving Cycle Generator

Welcome to CBDCCD system!!

Please enter information below to describe the relevant details to implement CBDCCD system.

ALL questions must be answered for the tool to work properly. If you do not know the answer to any one question, make an approximate educated guess.

Your Input

Social Demographics

Driver gender (male/female)

Driver age (in years, not driving age)

Household income (in Dollars)

Vehicle Features

Body type (e.g., sedan,suv,coupe,van,pickup,hatchback,convertible,wagon,other)

Fuel type (e.g., hybrid,gasoline,diesel,plug-in hybrid,natural gas,electric,other)

Vehicle age (in years, zero year for new cars)

Driving Needs

Commuter trip duration

Trip configuration (e.g., 13245, 12433, please look up the definition of micro-trips)



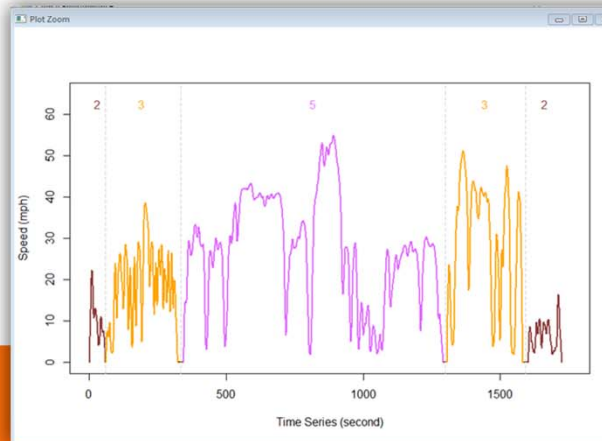
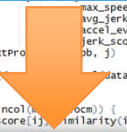
```

298
299
300
301
302
303
304
total_dura=length(y)
drive_dura=length(y[y!=0])
distance=sum(micro_trip_info$distance_total[tripp])
total_avg_speed=distance/total_dura*3600
drive_avg_speed=distance/drive_dura*3600

max_jerk_pos=max(y_jerk)*1.466667
avg_jerk_neg=mean(y_jerk[y_jerk<0])*1.466667
max_jerk_neg=min(y_jerk)*1.466667
root_mean_jerk=mean(sqrt(y_jerk[abs(y_jerk)>0]^2))*1.466667
accel_event=sum(micro_trip_info$ACCELEVENT[tripp]*micro_trip_info$distance_total[tripp])/distance
pct_idle=length(which(y_speed==5))/length(y_speed)
pct_accel=length(which((y_speed-5)/y_accel>5/30))+(y_speed-30)/y_accel<(-0.06))/length(y_speed)
length(y_speed)
th(y_range_accel[y_range_accel<0])
th(y_range_jerk[y_range_jerk<0])
micro_trip_info$distance_total[tripp])/distance
avg_speed,drive_avg_speed
avg_jerk_pos,max_jerk_pos,avg_jerk_neg,max_jerk_neg,root_mean_jerk
accel_event,pct_idle,pct_accel,pct_decel,pct_cruise,acc_score
jerk_score,k1_standard))
obj, j)
setTXTPro
data_set}},na.rm=T)
sim_score=0
for (ij in 1:ncol(similarity)) {
sim_score[ij]=similarity[ij,data_set,mn)
}
    
```

Proposed user interface

Programming in R



You are required to provide following information:
 Driver Gender (male or female): male
 Driver Age (year): 45
 Annual Household Income (\$): 90000
 Vehicle Body Type (e.g., sedan,suv,coupe,van,pickup,hatchback,convertible,wagon,other): sedan
 Fuel Type (e.g., hybrid,gasoline,diesel,plug-in hybrid,natural gas,electric,other): hybrid
 Vehicle age (year): 0
 Trip Duration (min): 30
 Trip Pattern Configuration (e.g., 1324, 12433): 23532
 How many candidate driving cycles do you want to observe: 20

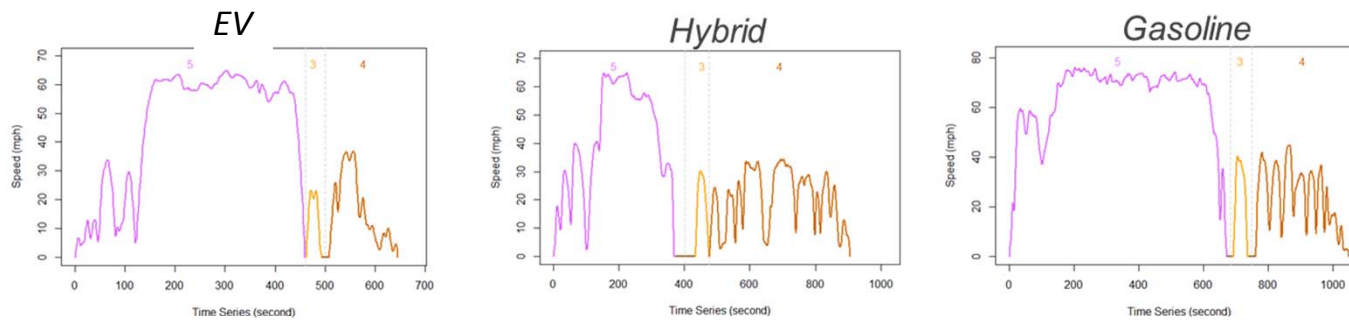
Generating candidate Driving Cycles...
 Calculating Similarity Score

| Born_ID | Similarity_Score | Candidate_ID |
|---------|------------------|--------------|
| 14 | 0.951585 | 1 |
| 17 | 0.9488914 | 2 |
| 5 | 0.9489735 | 3 |
| 8 | 0.9436362 | 4 |
| 3 | 0.9431129 | 5 |
| 12 | 0.9422522 | 6 |
| 10 | 0.9392650 | 7 |
| 6 | 0.9372243 | 8 |
| 2 | 0.9283185 | 9 |
| 4 | 0.9246588 | 10 |
| 1 | 0.9199240 | 11 |
| 7 | 0.9168057 | 12 |
| 18 | 0.9138316 | 13 |
| 20 | 0.9118079 | 14 |
| 19 | 0.9087745 | 15 |
| 11 | 0.9063459 | 16 |
| 16 | 0.9041400 | 17 |
| 9 | 0.8979091 | 18 |
| 13 | 0.8720869 | 19 |
| 15 | 0.8708573 | 20 |

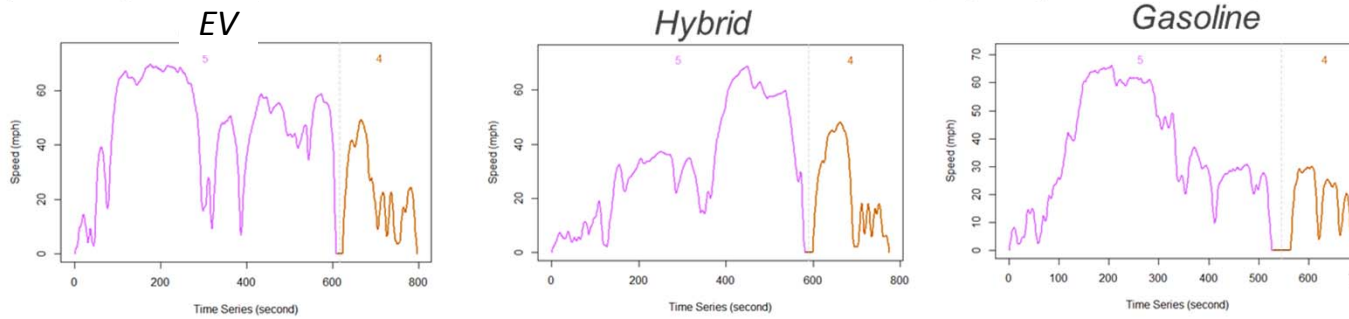
would you like to print the representative driving cycle?(y/n) y
 which other trip would you like to print? (Give the candidate ID):

Case Study: Driving cycles for EV and HV

(i) Driver Age: 40 ~50 yrs, Driver Gender: Male, Household Income: > \$150,000, Trip Length: 10~15 minutes, Micro Trips : 534



(ii) Driver Age: 40 ~50 yrs, Driver Gender: Female, Household Income: > \$150,000, Trip Length: 10~15 minutes, Micro Trips : 54



Driving cycle and fuel economy

- Two options to get fuel economy

Use VSP equation to calculate fuel consumed/emissions (Zhai, NCSU)

$$VSP = v \times (a + g \times \sin \phi + \psi) + \zeta \times v^3$$

Where:

v = vehicle speed (meters per second)

a = vehicle acceleration (meters per second square)

g = acceleration due to gravity (meters per second square)

ϕ = road grade

ψ = rolling resistance coefficient (meters per second square)

ζ = drag coefficient (reciprocal metres)

Use the cycles to predict MPG rating based on dynamometer tests



Summary

- AFV driving cycles have significant differences from conventional driving cycles
- Application
 - A Case Based System for Driving Cycle Design
 - Provide customers with more accurate estimation of fuel economy information
 - Make more informed vehicle purchase and use decisions



Thank YOU

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