NC STATE UNIVERSITY

METHODOLOGY FOR DEVELOPMENT OF A MODAL FUEL USE AND EMISSIONS RATE MODEL FOR A HYBRID ELECTRIC VEHICLE

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1. OBJECTIVES

- To quantify engine on/off operation rules for a selected hybrid electric vehicle (HEV) under hot stabilized conditions.
- To develop modal in-use exhaust emissions model for the HEV.
- To apply the engine rules and emissions model to predict emissions for selected standard driving cycles and link speed profiles measured under real-world traffic conditions.

2. EMPIRICAL DATABASE

Vehicle Parameters [a]

Vehicle	Toyota Prius
Model Year	2001
Odometer	58,140 miles
Hybrid Configuration	Series-Parallel
Engine Size	1.5 liter Gasoline
Emissions Standard	ULEV (2001)
Engine Rating	70 horsepower
Electric Motor Rating	44 horsepower

[a] Nam *et al.*, 2005.

- HEV dynamometer data measured via multiple Federal Test Procedure (FTP) test cycles were provided by the U.S. Environmental Protection Agency (EPA).
- Link speed profiles were collected using a Portable Emissions Measurement System (PEMS) in real-world traffic conditions in a previous project.

Empirical Database

Data Type	Driving Cycle	Data Resolution
Dynamometer	4-bag FTP	Second-by-second
PEMS	Link Speed Profile	Second-by-second

- 75% of data were used to calibrate the model and 25% of data were used for model validation.

Acknowledgement

Dr. Edward Nam at U.S. EPA provided hybrid electric vehicle dynamometer test data. The work was supported by U.S. EPA STAR Grant R831835 via the University of North Carolina - Chapel Hill. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not reflect the views of the EPA.

3. METHODOLOGY

Identification of Criteria for Engine Use

- A classification and regression tree (CART) is used to explore criteria for predicting when the engine is on.
  - Engine speed RPM is used as an indictor of engine on/off status. Speed and acceleration are used as predictors and RPM is predicted.
  - Based on analysis of second-by-second data, the HEV engine has a minimum RPM of approximately 500 when engine emissions occur.
  - Branches of the tree are added until the terminal nodes have values significantly different from 500 RPM.

Vehicle Specific Power Modal Emissions Model

- Apply a micro-scale vehicle specific power (VSP) based modal approach to estimate emissions based upon dynamometer test data.
  - Calculate VSP for each second of a speed profile.

$$VSP = v \times [1.1 \times a + 9.81 \times (\sin(\text{atan}(grade))) + 0.132] + 0.000302 \times v^3$$

Where: VSP = vehicle specific power (m^2/s^3);
v = speed (m/s);
a = acceleration (m/s^2);
$grade$ = road grade.

  - Categorize the second-by-second data based on VSP into discrete modes. Estimate modal average emissions while the engine is on.

Definition of Vehicle Specific Power Modes [b]

VSP Mode	Range (m^2/s^3)	VSP Mode	Range (m^2/s^3)
1	VSP<-2	9	16≤VSP<19
2	-2 ≤VSP<0	10	19≤VSP<23
3	0 <VS <1	11	23≤VSP<28
4	1≤VSP<4	12	28≤VSP<33
5	4≤VSP<7	13	33≤VSP<39
6	7≤VSP<10	14	VSP≥39
7	10≤VSP<13	Idle	VSP=0
8	13≤VSP<16		

[b] Frey *et al.*, 2002.

Emissions Predictions for Selected Driving Cycles and Link Speed Profiles

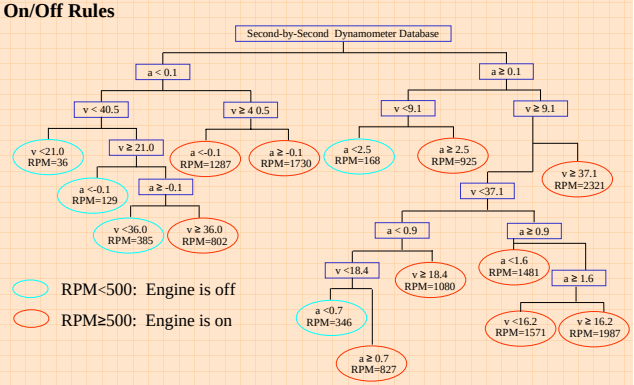
- Emissions estimated when the engine is on.
- Cycle and link average emission rates are estimated:

$$E_j = \sum_{i=1} \left\{ \frac{t_{i,j}}{T_j} \times ER_i \right\}$$

Where: $t_{i,j}$ = the time spent in VSP mode i for speed profile or driving cycle j, while the engine is on (sec);
T_j = total travel time (sec);
ER_i = modal average emission rates (g/s);
E_j = cycle or link average emissions (g/s).

4. RESULTS AND DISCUSSION

Classification and Regression Tree (CART) Modeling for HEV Engine On/Off Rules



Series-Parallel HEV Engine-Off Rules

Speed (v, mph)	Acceleration (a, mph/s)	Threshold Power [c] (mph^2/s)
0.0-9.1	a < 2.5	22.8
9.1-18.4	a < 0.7	12.9
18.4-36.0	a < 0.1	3.6
36.0-40.5	a < -0.1	-4.1

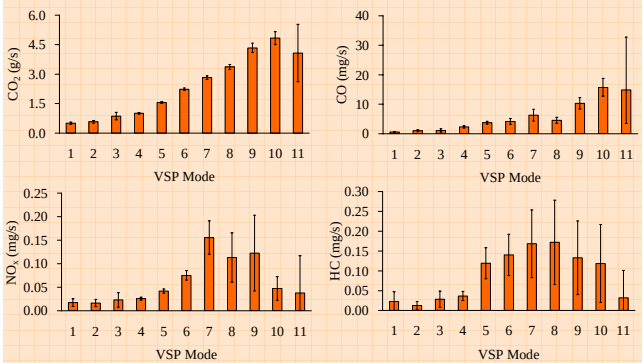
[c] Power=v×a

Validation of Engine-Off Rules [d]

Engine Off	Time in Cycle
Observed	59.5%
Predicted	60.8%

[d] Based on predictions for one 4-bag FTP cycle.

Modal Average Emission Rates



VSP Modal Average Emission Rates of A Hybrid Electric Vehicle based on Dynamometer Tests [e]

[e] No data were available for VSP Modes 12-14

- No data regarding how much power is drawn from the engine versus the battery are available, which may account for some inconsistent trends at high VSP.

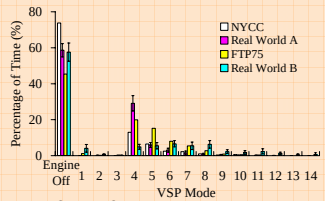
4. RESULTS AND DISCUSSION (con't)

Ratios of Modal Average Emission Rates for HEV vs. Selected Light-Duty Gasoline Vehicles (LDGVs) [f]

VSP Mode	CO_2	CO	NO_x	HC
1	0.30	0.07	0.02	0.05
2	0.39	0.26	0.03	0.05
3	0.76	0.34	0.07	0.07
4	0.45	0.28	0.02	0.08
5	0.53	0.34	0.02	0.22
6	0.63	0.25	0.03	0.20
7	0.69	0.32	0.05	0.20
8	0.73	0.16	0.03	0.18
9	0.84	0.29	0.02	0.12
10	0.86	0.29	0.01	0.08
11	0.62	0.13	0.01	0.02

[f] Average emission rates of LDGVs from Frey *et al.*, 2002.

Emissions Predictions for HEVs



Percentage of Time for Each VSP Mode and Predicted Engine Off for Selected Cycles

Predicted Average Emission Rates for Selected Driving Cycles

Speed Profile	Mean Speed (km/h)	CO_2 (g/s)	CO (mg/s)	NO_x (mg/s)	HC (mg/s)
NYCC	11.4	0.66	1.50	0.020	0.035
Real-World A	14.8	0.71	1.59	0.020	0.034
FTP-75	34.1	1.17	2.55	0.038	0.065
Real-World B	36.1	1.77	4.12	0.052	0.077

5. CONCLUSIONS

- The engine is off under threshold conditions of engine power demand that are speed and acceleration dependent.
- Modal average emissions generally increase with VSP modes except for NO_x and HC.
- Emissions comparisons between HEV and LDGV imply that the use of HEV can reduce emissions.
- Cycle or link average emissions are estimated to increase with mean speeds for selected cycles.
- Data regarding battery charging and discharging, and use of the electric motor, are needed in order to develop an improved model.
- Engine and emissions modeling are recommended for further application as more data for a large number of HEVs are available, particularly in real-world traffic conditions.