Incorporating Drivability Metrics into Optimal Energy Management Strategies for Hybrid Vehicles - Supplemental Data

Abstract

This is a web-based supplement to a two-part paper on hybrid vehicle energy management [1], [2]. It contains data that was cut from for length. Brief descriptions are included, but most of the explanations are in [1], [2].

I. Robustness to Real-World Driving

This section contains supplemental data for the section of the same name in [1] (Sec. II). The figures here primarily validate performance across different ensemble sets and different simulation methods. They also allow detailed comparisons of cross-sensitivity to different design and testing cycles. The data presented here supplement the data in the published papers and do not show any new trends but are included for the interested reader.

Recall that two methods are used to simulate the controllers:

- **Concatenated Cycles** - The ensemble of 100 cycles is assumed to represent one vehicle's driving history, about 1000 miles. The starting SOC of the first trip is 0.5, and the starting SOC for each subsequent trip is the ending SOC of the previous trip.
- **Individual Cycles** - Each cycle is studied individually, and the starting SOC for each trip is 0.5.

The ensemble set is first assumed to represent a single vehicle and treated as a Concatenated Cycle. Fuel economy and final SOC results are shown in Fig. 1. The figure shows five controllers evaluated on Ensembles 1 and 2: the baseline controller and 4 SPSDP controller families designed on statistics from FTP, NEDC, Ensemble 1 and Ensemble 2.

The cycles in each ensemble are also treated as individual trips, where the SOC always starts at 0.5. The weighted average of fuel economy compared to Engine Events is shown in Fig. 2 for Ensembles 1 and 2.

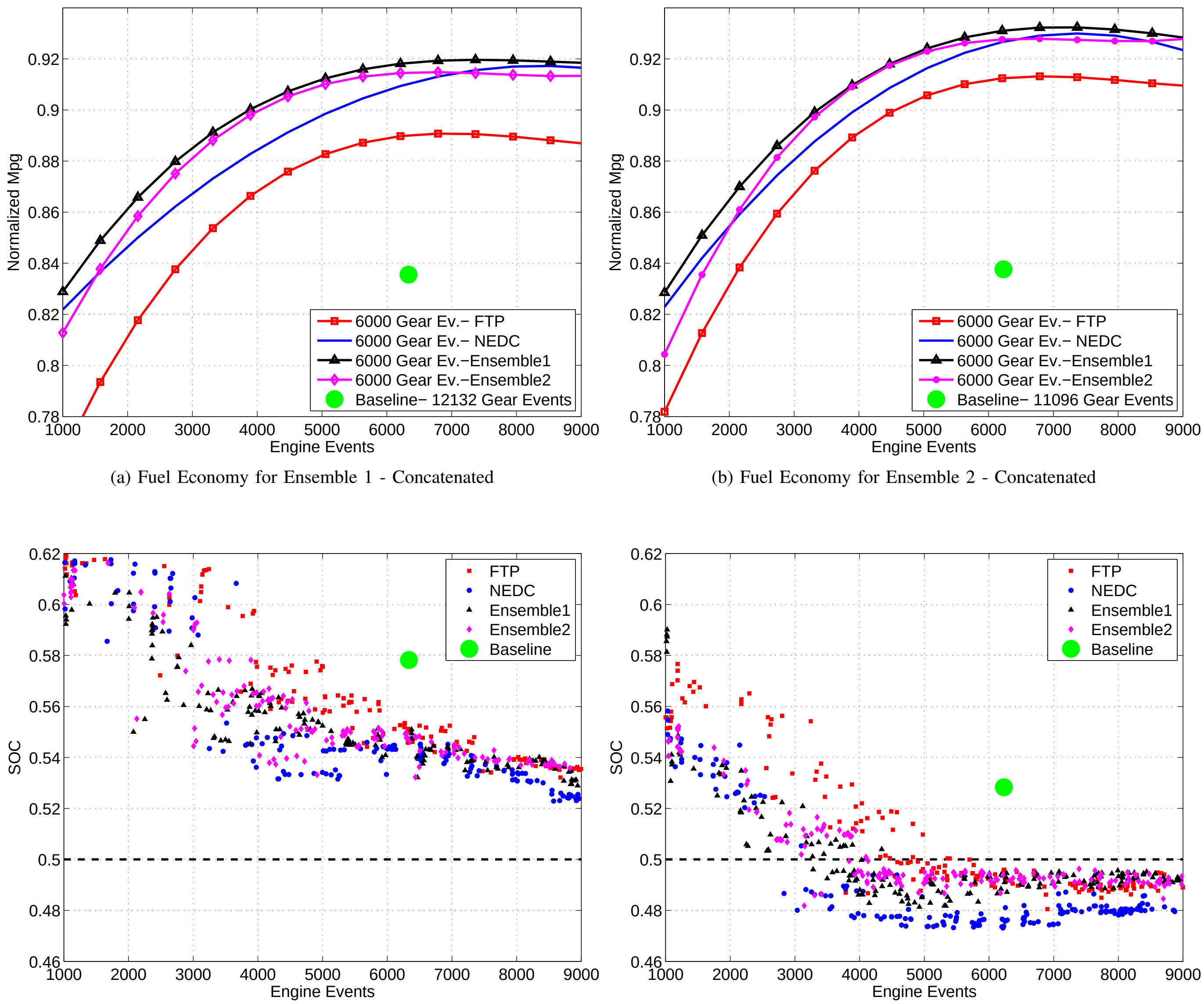
II. Drivability on Government Test Cycles

This section reprints Figure 6 in [1] with additional data. Specifically, the linear curve fitting data is included for the lines drawn in Figs. 3b and 3e.

References

[1] D. Opila, X. Wang, R. McGee, R. Gillespie, J. Cook, and J. Grizzle, "Incorporating drivability metrics into optimal energy management strategies for hybrid vehicles Part 1: Model, methods, and government drive cycles," *Submitted to IEEE Transactions on Control Systems Technology*, 2010.

[2] ——, "Incorporating drivability metrics into optimal energy management strategies for hybrid vehicles Part 2: Validation and real-world robustness," *Submitted to IEEE Transactions on Control Systems Technology*, 2010.



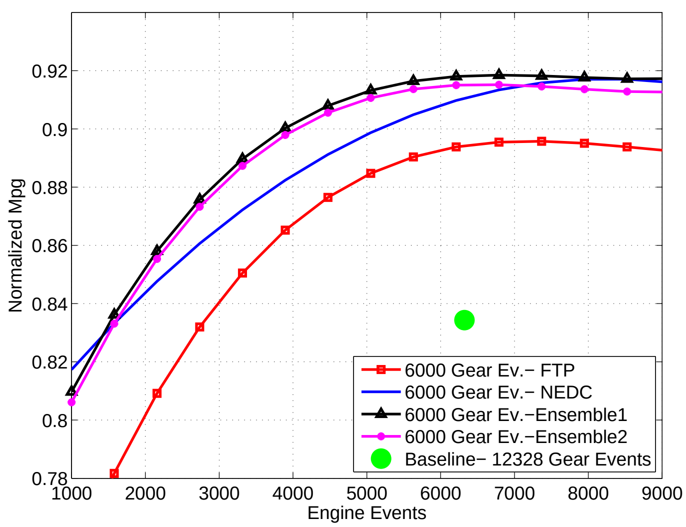
(a) Fuel Economy for Ensemble 1 - Concatenated

(b) Fuel Economy for Ensemble 2 - Concatenated

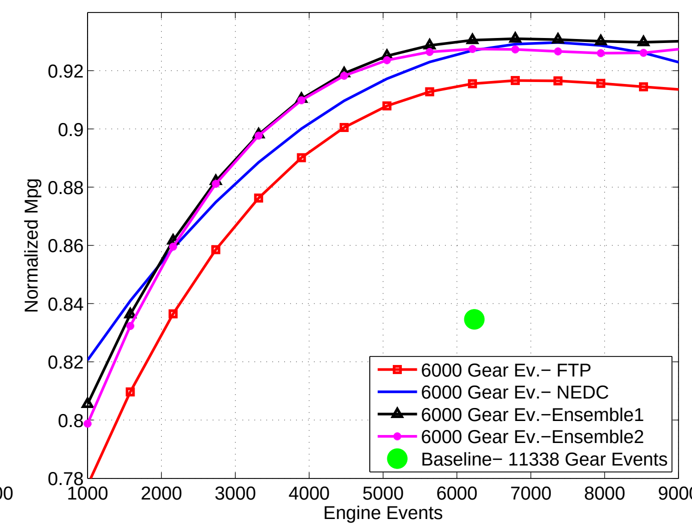
(c) Final SOC for Ensemble 1 - Concatenated

(d) Final SOC for Ensemble 2 - Concatenated

Fig. 1: Fuel Economy, final SOC, and Drivability Metrics on the concatenated real-world drive sets for the baseline controller and SPSDP controller *families* designed with statistics from FTP, NEDC, *Ensemble 1*, and *Ensemble 2*. Fuel Economy, Gear Events, and Engine Events are cumulative with the ensemble set treated as a single trip of approximately 1000 miles. Results are normalized to the baseline controller on FTP, as in [1].

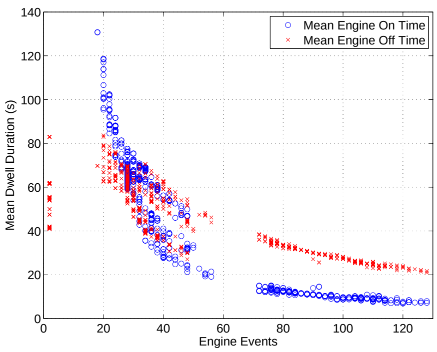


(a) Fuel Economy for Ensemble 1 - Individual Cycles

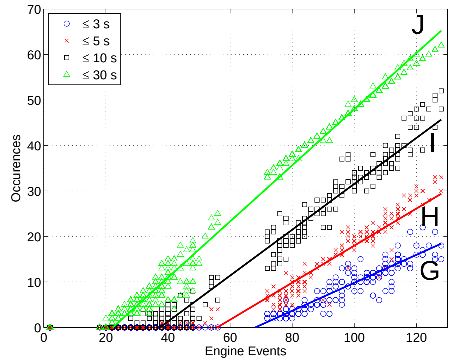


(b) Fuel Economy for Ensemble 2 - Individual Cycles

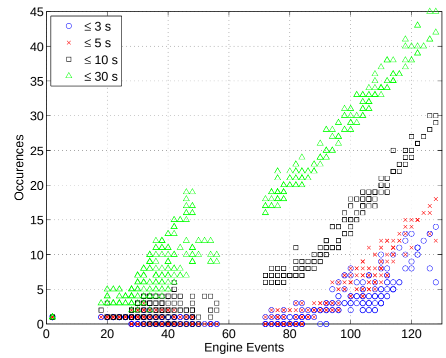
Fig. 2: Fuel Economy and Drivability Metrics on the ensembles when simulated as individual cycles for the baseline controller and SPSDP controller *families* designed with statistics from FTP, NEDC, *Ensemble 1*, and *Ensemble 2*. Fuel Economy, Gear Events, and Engine Events are cumulative for the whole cycle set, representing approximately 1000 miles. Results are normalized to the baseline controller on FTP, as in [1].



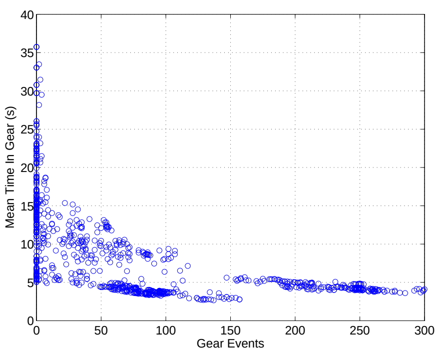
(a) Mean engine on and off durations compared to *Engine Events*.



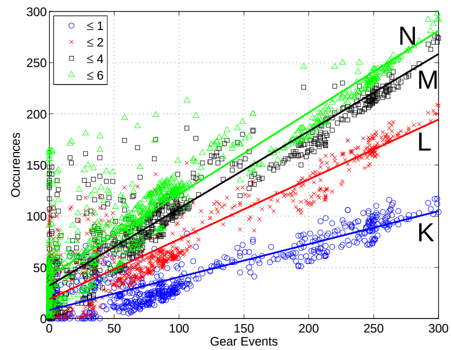
(b) Engine on durations less than some number of seconds compared to *Engine Events*. Data are shown for cutoffs of 3, 5, 10, and 30 seconds.



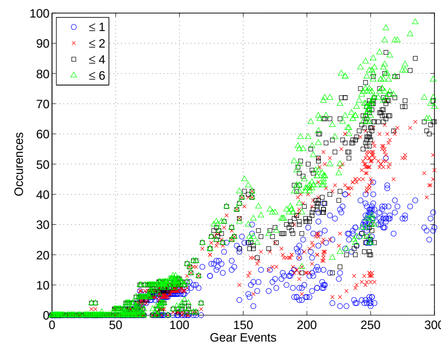
(c) Engine off durations less than some number of seconds. Data are shown for cutoffs of 3, 5, 10, and 30 seconds compared to *Engine Events*.



(d) Mean dwell time in gear between shifts or clutch disengagements compared to *Gear Events*.



(e) Gear dwell times less than some number of seconds between shifts or clutch disengagements compared to *Gear Events*. Data are shown for cutoffs of 1, 2, 4, and 6 seconds.



(f) Gear hunting events that occur within some number of seconds. This is a sequential upshift/downshift or upshift/downshift that occurs within a set period of time. Data are shown for cutoffs of 1, 2, 4, and 6 seconds in comparison to *Gear Events*.

Label	Metric	Straight-line fit	σ	Range
G	On≤3	$\hat{y} = 0.31x - 20.9$	0.90	0-25
H	On≤5	$\hat{y} = 0.41x - 22.7$	1.37	0-35
I	On≤10	$\hat{y} = 0.50x - 18.9$	1.63	0-55
J	On≤30	$\hat{y} = 0.62x - 13.7$	2.01	0-65

(g) Curve fitting for engine on durations from subfigure 3b. σ is the standard deviation between the data and the fit.

Label	Metric	Straight-line fit	σ	Range
K	In Gear≤1	$\hat{y} = 0.32x + 8.25$	13.8	0-120
L	In Gear≤2	$\hat{y} = 0.58x + 19.0$	20.5	0-210
M	In Gear≤4	$\hat{y} = 0.75x + 32.1$	24.1	0-280
N	In Gear≤6	$\hat{y} = 0.80x + 41.5$	26.4	0-300

(h) Curve fitting for gear dwell times from subfigure 3e. σ is the standard deviation between the data and the fit.

Fig. 3: Comparison of simple and complex drivability metrics on the FTP cycle. Complex engine activity metrics are compared to the simplified *Engine Events* metric in subfigures 3a-3c. Three gear activity metrics are compared to the simplified *Gear Events* metric in subfigures 3d-3f. Subfigures 3b and 3e have straight-line fits to the data, and the parameters are shown in Tables 3g and 3h.