02FCC-27

# Fuel Economy Improvement via Hybridization vs. Vehicle Performance Level

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## ABSTRACT

Although many of the studies that use vehicle simulation models to estimate fuel economy gains for a range of hybrid vehicles have attempted to control for the comparability of performance between conventional and hybrid vehicles, different rules and simulation models have been used. This paper reviews the estimates of city, highway, and corporate average fuel economy gain vs. varying measures of performance change for a set of those studies. We examine the causes for the wide range in estimates when hybridizing a vehicle, establish a database, and provide detailed discussions of relationships using several of the studies. Statistical models developed on the basis of the data reveal the causes of variation in mpg gain among conventional/hybrid pairs that have the same 0–60 mph acceleration times. Our study reveals that potential mpg gain via hybridization is greater as the 0–60 mph acceleration time of the pair of compared vehicles drops (and power-to-weight ratios increase). We demonstrate that engine downsizing is necessary to obtain large benefits, and that an increase in electric motor power relative to engine power — up to a point — improves the fuel economy of hybrids.

## INTRODUCTION

Two hybrid passenger cars — the Toyota Prius and Honda Insight — are commercially available in the United States today, and hybrid light-duty trucks and sport utility vehicles (SUVs) are planned by Ford, GM, and DaimlerChrysler within approximately three years. Ford plans to introduce a hybrid version of the Escape, its smallest, most fuel-efficient SUV. DaimlerChrysler plans a hybrid version of its Dodge Durango, and GM plans a hybrid variant of its Silverado pickup truck (1). Furthermore, as of the writing of this paper, Honda had stated that it would make a hybrid drivetrain available in its Civic line, making use of the technology developed for the Insight. The Prius and the Insight are only available with a hybrid drivetrain. However, the planned models listed above will each have a hybrid drivetrain option; the automakers expect that only a fraction of the model line will be sold as hybrids. The Prius, and especially the Insight, include features other than the hybrid drivetrain that improve fuel economy. Until the new models become available, it will not be possible to develop a controlled comparison between a commercial conventional vehicle (CV) and a comparable vehicle differing only in terms of the hybrid drivetrain.

Each of the hybrids listed above uses only gasoline as a fuel and cannot plug into the grid to use electric power. Such organizations as the Electric Power Research Institute (EPRI) and the California Air Resources Board (CARB) have promoted hybrids that can be connected to the grid (2). CARB has written regulations that provide incentives for the introduction of grid-connectable hybrids with 10 or more miles of all-electric range. The regulations establish a sliding scale of benefits from 10 to 120 miles of all-electric range. So grid-connectable hybrids are also of considerable interest, although no major manufacturer has indicated its intention to produce a grid-connectable hybrid with an all-electric range of 10 or more miles.

This paper draws upon simulations of theoretical pairs of conventional and hybrid vehicles to address the issue of comparable performance comparison. The studies compared in this paper include a range of 0–60 mph performance values (from 14 to 8 seconds), allowing us to provide insight into the relationship of 0–60 mph performance to the mpg benefits of hybridization. Although the time required to accelerate from 0–60 mph in conventional/hybrid vehicle pairs is held constant, top speed and gradeability are allowed to drop in the hybrid vehicle so that the size of the engine may be reduced and greater gains in fuel economy obtained. This is an important design choice that will inevitably affect consumer preferences for the hybrid vs. the conventional vehicle.

DISCUSSION OF CONVENTIONAL VS. HYBRID COMPARISONS IN LITERATURE SURVEYED - We located six studies that use 0–60 mph performance as the "anchor" for comparing pairs of conventional and parallel hybrid vehicles with the same body, differing only with respect to the conventional vs. hybrid drivetrain (2–7). Four of these six studies use vehicle simulation models to predict 0–60 mph acceleration time (2–5). Some or all of the funding for these four studies was provided by the U.S. Department of Energy (DOE). Three of the four use the same model — the Advanced Vehicle Simulator (ADVISOR) developed at the National Renewable Energy Laboratory (NREL) (8,9) — although different versions of ADVISOR were used in each study (2–4). Three of the four were conducted at Argonne National Laboratory (3–5) and one at EPRI, with vehicle simulations prepared by an NREL staff member (2). One of the six vehicle simulation studies, conducted at MIT, does not estimate 0–60 mph acceleration time, but holds peak powertrain kW per kg of vehicle mass constant (6). The MIT study only investigated grid-independent hybrids.

Investigation of the vehicle simulations for grid-independent hybrids (in the four studies that employed vehicle simulations) indicates that the assumption that equivalent kW/kg values will obtain the same 0-60 mph acceleration time is approximately correct (less than 2% error, for an average of 13 vehicles). For the six pairs examining grid-connected hybrids, this is not the case, and a notably lower peak kW/kg value for the hybrids (11% less) is estimated to obtain the same 0–60 mph acceleration time (electric motors have considerably higher starting torque than engines of the same peak kW). The sixth study (7) was based on attempting to adjust the attributes of the conventional and hybrid vehicle so that 0–60 mph acceleration times would be equivalent; this study employed approximations from conventional gasoline vehicles to develop the adjustment needed for the hybrid vehicle. Other sources demonstrate that, based on vehicle simulation models, this method understates the fuel economy benefit of hybridization (10).

We found two other studies that compared selected hybrid and fuel cell vehicles to conventional vehicles (11, 12). Information on 0–60 mph acceleration times was not presented in these studies. However, peak kW values for power units, motors, reformers, and battery packs — as well as mass of the vehicle, rolling resistance, coefficient of drag, and frontal area — were provided. Construction of the kW/kg ratio indicated that the conventional vehicle had a value of about 0.077, in comparison to about 0.055 for the advanced vehicles in the 1998 study (12), and 0.063 in the 1999 study (11). Evaluation of the kW/kg values in the database assembled for this study will show that the difference in 0–60 mph acceleration times between the conventional and advanced vehicles in the 1998 study would have been nearly 4 seconds, and in 1999 nearly 3 seconds. This difference is unacceptable according to the rules adopted by the six studies whose results are included here. In any case, these two studies did not include a gasoline-fueled hybrid.

Another well-publicized study that compares hybrids and conventional vehicles is the General Motors (GM)-sponsored study on well-to-wheels energy use and greenhouse gas emissions of advanced fuel/vehicle systems, conducted jointly by staff of Argonne National Laboratory, GM, Shell, BP, and Exxon (13). The vehicle simulations, however, were the exclusive responsibility of GM. This study differs from the others discussed here in several respects. It examines a specific contemporary pickup truck (Chevrolet Silverado) rather than a hypothetical future passenger car. Excepting while defining 80$^{th}$ percentile cases, it does not include any cases in which the vehicle body mass is reduced. In most of the other studies used here, the mass, rolling resistance, and coefficient of drag of the hybrid vehicles are less than those of conventional vehicles. The GM performance requirements were based on their interpretation of customer requirements, with top speed maintained at 110 mph. This requirement generally prevented engine downsizing and constrained the fuel economy gains that could be obtained. In the GM study, the 0-60 mph acceleration time of the hybrid was a very rapid 6.3 seconds, in comparison to 7.9 seconds for the base conventional truck. Thus, while the studies by Thomas et al. (11,12) compare slower advanced vehicles to the conventional vehicle, GM's does the opposite. Finally, the GM study did not document the needed characteristics of components or vehicle mass changes caused by the drivetrain switches, so the database constructed here could not have included the appropriate GM case.

DISCUSSION OF ATTRIBUTES OF AVERAGE VEHICLES IN THE DATABASE - The attributes of each of the vehicles used in our database are listed in Table 1. The vehicles can be sub-grouped into non-grid hybrids, and grid-connectable hybrids capable of operating in an all-electric mode for 20 miles or more. As a benchmark reference, we include the base non-grid case from the EPRI study — a case designed to represent the body configuration of a contemporary mid-size car. The table shows that the average vehicle in the sample is lighter than today's mid-size car, has a lower performance level (kW/kg), lower coefficient of drag (Cd), lower rolling resistance (Cr), and a slightly reduced frontal area. Although the non-grid hybrids require slightly less peak kW per kg than their counterpart conventional vehicles, they actually require a slightly more powerful drivetrain, because the increase in hybrid vehicle mass more than offsets the high low-rpm torque capability of the electric motors. For the grid-connected hybrids, however, the large motors and high low-rpm torque are estimated to allow a lower total peak kW rating, despite significant mass increases.

The ratio of fuel consumed by the hybrid to fuel consumed by the conventional vehicle is lowest in city

driving (the Federal Test Procedure [FTP]) and highest in the highway driving cycle. Composite (COMP) cycle results, based on 55% city cycle fuel consumption and 45% highway cycle fuel consumption, are intermediate. The grid-connectable hybrids have larger motors and smaller engines than the non-grid hybrids, accelerate more rapidly, and achieve greater reductions in fuel consumption.

Table 1 Attributes of Vehicles in Sample (Refs. 2-6)

| | 0-60 mph Time (s) | kW/kg CV | kW/kg HEV | HEV/CV gpm City | HEV/CV gpm COMP | HEV/CV gpm Hwy |
|---|---|---|---|---|---|---|
| Grid-Independent (n = 14) | | | | | | |
| Mean | 10.6 | 0.065 | 0.064 | 0.64 | 0.71 | 0.85 |
| Std. Dev. | 2.0 | 0.013 | 0.013 | 0.08 | 0.08 | 0.11 |
| Range | 6.0 | 0.043 | 0.042 | 0.28 | 0.27 | 0.32 |
| Min. | 8.0 | 0.042 | 0.042 | 0.48 | 0.56 | 0.66 |
| Max. | 14.0 | 0.085 | 0.085 | 0.75 | 0.83 | 0.99 |
| Grid-Connectable (n= 6) | | | | | | |
| Mean | 8.5 | 0.079 | 0.071 | 0.54 | 0.60 | 0.74 |
| Std. Dev. | 0.5 | 0.007 | 0.007 | 0.03 | 0.04 | 0.10 |
| Range | 1.0 | 0.015 | 0.018 | 0.08 | 0.10 | 0.23 |
| Min. | 8.0 | 0.070 | 0.064 | 0.49 | 0.56 | 0.65 |
| Max. | 9.0 | 0.085 | 0.082 | 0.57 | 0.66 | 0.88 |
| Total Sample (n = 20) | | | | | | |
| Mean | 10.0 | 0.069 | 0.066 | 0.61 | 0.68 | 0.82 |
| Std. Dev. | 2.0 | 0.013 | 0.012 | 0.08 | 0.09 | 0.12 |
| Range | 6.0 | 0.043 | 0.042 | 0.28 | 0.27 | 0.34 |
| Min. | 8.0 | 0.042 | 0.042 | 0.48 | 0.56 | 0.65 |
| Max. | 14.0 | 0.085 | 0.085 | 0.75 | 0.83 | 0.99 |
| EPRI Grid-Independent Base Case | | | | | | |
| | 9.0 | 0.0755 | 0.0692 | 0.57 | 0.69 | 0.95 |

| | CV kg | HEV kg | CV kW | HEV kW | HEV Engine kW | Cd | A ($m^2$) | Cr |
|---|---|---|---|---|---|---|---|---|
| Non-Grid Hybrid (n=14) | | | | | | | | |
| Mean | 1300 | 1378 | 85 | 88 | 57 | 0.27 | 2.06 | 0.0074 |
| Std. Dev. | 137 | 132 | 23 | 21 | 13 | 0.03 | 0.10 | 0.0010 |
| Range | 546 | 449 | 72 | 64 | 40 | 0.11 | 0.40 | 0.0035 |
| Min. | 1136 | 1154 | 55 | 60 | 42 | 0.22 | 1.80 | 0.0055 |
| Max. | 1682 | 1603 | 127 | 124 | 82 | 0.33 | 2.20 | 0.0090 |
| Grid-Connectable (n=6) | | | | | | | | |
| Mean | 1478 | 1574 | 117 | 111 | 47 | 0.28 | 2.12 | 0.0073 |
| Std. Dev. | 159 | 118 | 11 | 10 | 10 | 0.04 | 0.06 | 0.0009 |
| Range | 316 | 328 | 29 | 29 | 27 | 0.08 | 0.11 | 0.0025 |
| Min. | 1366 | 1439 | 98 | 99 | 34 | 0.25 | 2.06 | 0.0055 |
| Max. | 1682 | 1767 | 127 | 128 | 61 | 0.33 | 2.17 | 0.0080 |
| Total Sample (n=20) | | | | | | | | |
| Mean | 1354 | 1437 | 95 | 97 | 54 | 0.27 | 2.08 | 0.0074 |
| Std. Dev. | 163 | 156 | 25 | 20 | 13 | 0.03 | 0.09 | 0.0009 |
| Range | 546 | 613 | 72 | 64 | 48 | 0.11 | 0.40 | 0.0035 |
| Min. | 1136 | 1154 | 55 | 64 | 34 | 0.22 | 1.80 | 0.0055 |
| Max. | 1682 | 1767 | 127 | 128 | 82 | 0.33 | 2.20 | 0.0090 |
| EPRI Grid-Independent Base Case | | | | | | | | |
| | 1682 | 1603 | 127 | 111 | 67 | 0.33 | 2.17 | 0.0080 |

The range of attribute values for the 14 non-grid hybrid cases is consistently far wider than the range for the six grid-connectable hybrids. Accordingly, the studies of the 14 non-grid hybrids provide a much better opportunity to statistically assess the determinants of fuel consumption reduction (fuel economy gain) through varying degrees of hybridization for varying levels of vehicle performance.

The primary question addressed by the experiments here is "what is the expected fuel economy gain obtainable on the composite test and its city and highway components when switching from a conventional to a hybrid drivetrain in a given vehicle body?" One might stop at constructing an average on the basis of existing studies and use the mean value. The reality however, is that there is a wide range of values technically possible, and no single number can be said to be representative.

Both the MIT and the GM studies introduced the notion of uncertainty in estimates of fuel economy gain when adopting advanced vehicle technologies. Both provide a judgmental measure of the range of uncertainty, but in each study, only one set of experiments (one set of components and performance requirements) is conducted for the gasoline conventional vehicle vs. the hybrid case. In the "base" case, GM predicts a composite fuel consumption reduction of 17%, while MIT predicts 31%. The GM hybrid, from the context of the discussion, probably has little or no engine downsizing. MIT's hybrid demonstrates a reduction in engine peak power of 32%, almost identical to the 33% average for the 14 non-grid hybrids listed in Table 1.

The average fuel consumption reduction for the non-grid hybrids listed in Table 1 is 29% — almost identical to the MIT estimate — with a two standard deviation range from 13% to 45% (a very wide range). We will show later, however, that the MIT estimates, adjusted statistically, are actually less optimistic than the sample as a whole. Although the uncertainty range in the GM study is only presented in the aggregate (in a graph for the full fuel cycle), it appears that the uncertainty range recommended by MIT is narrower than plus or minus 16% from the mean implied in Table 1. Both MIT and GM appear to estimate an asymmetrical uncertainty around the mean, with GM's estimate being much more skewed from the normal than MIT's. The GM estimates of uncertainty are hard to interpret. By cross-comparing GM's 20% and 80% probability values, we obtain a range of estimates from a gain in fuel consumption of 18% to a reduction of 37%. If we only compare *within* the 20%, 50%, and 80% probability values (rather than across) for the conventional and hybrid vehicles, the range narrows to 14% to 17%. In fact, it seems likely that the reasonable range for a given type of powertrain meeting a set of performance constraints should be closer to the latter than the former uncertainty range

estimate. As is demonstrated below, a great deal of the two-standard-deviation scatter around the average in this sample is statistically explainable, indicating that the uncertainty range is far less than plus or minus 16% from the mean.

## METHOD

We construct several multiple regression models to compare gasoline parallel hybrid vs. comparable conventional gasoline passenger car fuel economy gain estimates in five studies:

1. *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*, Graham et al. (2) (5 pairs)
2. *Hybrid Vehicle Technology Assessment*, Plotkin et al. (3) (9 pairs)
3. *Estimating Trade-Offs Along the Path to the PNGV 3X Goal*, Santini et al. (4) (1 pair)
4. *Hybrid Options for Light-Duty Vehicles*, An, Stodolsky, and Santini (5) (4 pairs)
5. *On the Road in 2020*, Weiss et al. (6) (1 pair)

From these studies, we compiled a database of the estimated fuel economy gains (or fuel consumption reduction, as in Table 1) for pairs of conventional and hybrid electric vehicles designed to have the same 0–60 mph acceleration times. These 0–60 mph acceleration times for the pairs in the resulting database vary from 14 to 8 seconds. We determined from this sample (Table 1) that the 0–60 mph acceleration time of both non-grid hybrids and conventional vehicles related to nearly equal values of peak kW/kg of vehicle mass, though hybrid peak kW/kg was consistently a bit less (average of <2%). For the grid-connectable hybrids, the difference was notable, averaging over 10%.

As a surrogate for the 0–60 mph acceleration time of the pair, we used the conventional vehicle peak kW/kg in the statistical models predicting fuel economy (the statistic k [defined below]); we also developed a separate statistical model of fuel consumption using the 0–60 mph acceleration time of the pair. The simulated vehicles also varied in the degree to which they depend on electric drive vs. conventional drive. As a summary statistic to represent this variation, the ratio of peak motor power to peak engine power was used (the statistic m [defined below]).

Vehicle attributes in the three studies varied. An, Stodolsky, and Santini (5) and MIT (6) examined compact cars, while the other two studies modeled mid-size cars. (Although MIT states that it modeled mid-size cars, the frontal area of the compared vehicles was dropped from an initial 2.0 to 1.8 $m^2$ — less than the subcompact Honda Insight's 1.9 $m^2$). The Plotkin et al. study (3) employed a conventional four-cylinder fuel-injected Saturn engine in its hybrid simulations and used manual transmissions in its hybrid and conventional vehicle simulations. The Graham et al. study (2) used an Atkinson-cycle engine (like that used in the Prius) in its hybrids and a manual transmission. The An, Stodolsky, and Santini (5) study assumed a Prius drivetrain for the FHV (full hybrid vehicle with a large share of peak power via electric drive (10)) case (Atkinson engine and unique continuously variable transmission [CVT]) and a conventional engine and automatic transmission in the MHV (mild hybrid vehicle with a small share of peak power via electric drive (10)) case. Plotkin et al. examined both FHV and MHV cases, while Graham et al. investigated only FHV cases. Only Plotkin et al. and Graham et al. included cases with grid- connectable hybrids that could run acceptably for 20 or more miles in an all-electric mode. Variables constructed and used in regression tests included the following:

g = cycle mpg gain = (mpg of HEV)/(mpg of CV) – 1

$R_d$ = hybrid's cycle gal/mi percent of conventional vehicle's = 100x [(gpm of HEV)/(gpm of CV) – 1], where d indicates the driving cycle, either city/urban driving (u), highway driving (h), or composite – COMP—based on 55% city and 45% highway fuel use (c)

t = 0–60 mph acceleration time (in seconds)

e = percent reduction in engine peak power from the conventional to the hybrid vehicle

k = (peak kW of CV)/(mass of CV)

m = (motor peak kW of HEV)/(engine peak kW of HEV)

a = variable indicating that HEV has an Atkinson cycle engine and CVT (1 if yes, 0 if no)

F = variable indicating estimate is from *Ref.5* (1 yes, 0 no)

G = variable indicating estimate is from *Ref. 2* (1 yes, 0 no)

W = variable indicating estimate is from *Ref. 6* (1 yes, 0 no)

S = variable indicating estimate is from *Ref. 4* (1 yes, 0 no)

$C_d$ = coefficient of drag of both the HEV and CV in the pair

A = frontal area of both the HEV and CV in the pair

$C_r$ = coefficient of tire rolling resistance of both the HEV and CV in the pair

E = variable indicating HEV motor kW > engine kW (1 yes, 0 no)

GRADEABILITY AND SUSTAINABLE TOP SPEED - Two performance measures affected by peak kW/kg are

continuous gradeability and sustainable top speed. There was not enough information published in the studies surveyed to conduct statistical analysis of the determinants of these variables. Only the Graham et al. study published estimates of sustained top speed, and only GM (13) used top speed as a performance constraint. Of the studies used, 2–4 estimated gradeability, though different gradeability standards were used.

## REGRESSION ESTIMATES

SIMPLE TWO-VARIABLE REGRESSION MODEL - We start with a simple summary model of reductions in composite fuel consumption ($R_C$) as a function of engine peak power reduction (e) and 0–60 mph acceleration time (t) for all 20 vehicle pairs (Table 2).

Table 2 Simple Regression Model of Percent Hybrid Fuel Consumption Compared to CV (gal/mi)

| | | | |
|---|---|---|---|
| $R_c$ = | 50.3 | +2.61•t | +0.21•e |
| | (6.71)[a] | (4.66) | (3.48) |
| | $R^2$ = 0.86 | | N = 20 |

[a] Values in parenthesis represent t-statistics

This simple equation indicates that 86% of the sample variance can be summarized by two vehicle pair attributes. It provides a summary of the major implications of this study — namely, that the potential savings through hybridization are strongly related to (1) the performance level of the base vehicle that is being hybridized, and (2) the degree of engine downsizing that is adopted. A problem with this equation is that it is too much of a simplification to be informative about hybrid vehicle design. For example, many combinations of engine size and motor/battery pack size are consistent with a given 0–60 mph acceleration time, but each will provide a different level of reduction in fuel consumption (increase in fuel economy).

IMPLICATIONS FOR A CASE WITH NO ENGINE DOWNSIZING - We can plug an educated guess for the GM case into this equation. First, we assume no engine size change. We note that the base 0–60 mph acceleration time is 7.9 seconds. The result is an estimated 29% reduction in fuel consumption, compared to GM's estimate of 17%. While this estimate is greater than the GM estimate, the hybrid in the GM case accelerates from 0–60 mph in 6.3 seconds (a characteristic resulting from GM's multi-attribute interpretation of customer requirements), so this case is not comparable to the cases for which the regression was estimated. To have a comparable case, the engine size in the hybrid would have to be reduced. The regression equation above can be solved to imply that the engine size reduction needed to slow the 0–60 mph acceleration time of the hybrid to 7.9 seconds would be about 60%, which would significantly compromise other performance attributes of the vehicle, and require a very large motor and battery pack.

HYPOTHESES FOR A MORE COMPLEX MODEL - The intention of this study is to develop summaries of major design attributes of hybrid vehicles that are associated with improvements in fuel economy resulting from a switch to a hybrid powertrain in an otherwise equivalent vehicle body. One of the major design choices is the "degree" of hybridization. How far along a continuum from no power provided by a motor and battery pack (a conventional vehicle) to all power provided by a motor and battery pack (an electric vehicle) does the designer wish to go when adopting a hybrid powertrain? Is it true that the further along that continuum, the greater the improvement in fuel economy? Do returns to improvements in fuel economy diminish as designers move along that continuum? When adding battery packs and larger motors to allow all-electric operation, the added mass must be moved by a gasoline-powered engine until the vehicle is switched to all-electric operation. In this study, we only look at gasoline fuel economy. Despite the negative effect of added battery mass, there is a beneficial effect because the larger battery and motor allow greater reduction in the engine size and allow for more regenerative braking. The net effect is not obvious.

REDUCING ENGINE SIZE IN HYBRIDS - Another issue is how far the engine size can drop before affecting consumer acceptability. In the EPRI study, researchers estimated for the base vehicle case, in which the hybrid vehicle of the pair had 60 miles of all-electric range and could sustain a speed of 97 miles per hour (2). The engine in this hypothetical EPRI hybrid vehicle with 9 second 0-60 mph acceleration capability was downsized by 70% —close to the 60% that was estimated to be necessary to move the GM hybrid from a 6.3s 0–60 mph acceleration capability to a 7.9s capability. Consistent with the fact that the EPRI hybrid's engine size dropped more than for the GM case adjustment, the composite fuel consumption of the EPRI case dropped by 36%, more than the estimated 29% for the GM case. Based on the EPRI example here, if the GM requirement that the hybrid vehicle be capable of a sustained top speed of 110 mph, the engine would not have been downsized so dramatically, and the fuel efficiency would not have been as good. Further, assuming the same battery and motor characteristics, the hybrid in this case would have to accelerate to 60 mph faster than the base conventional vehicle, as was true in the GM analysis.

VEHICLE LOADS (MOTIVE POWER REQUIREMENTS) RELATED TO BODY ATTRIBUTES - Other factors that may affect the benefits of hybridization are the attributes of the vehicle body. In some preliminary analyses of the Plotkin et al. (3) and Graham et al. (2) results, we observed that there appeared to be a greater benefit of hybridization as the load on the vehicle decreased (14, p. 15). There are several causes of "load" that a vehicle

must overcome to move. The equations of motion for vehicles include mass, $C_d$, A, and $C_r$ as key determinants. Aerodynamic drag load (power) is a function of the product of $C_d$ and A and of the cube of velocity. Because of the strong effects of velocity, any effects of aerodynamic drag should be greater on cycles with higher average speed. Load from the rolling resistance of tires is a function of mass times $C_r$ and is linear to velocity. Combinations of the variables $C_d$, A, and $C_r$ were tested in different statistical experiments. The product of $C_d$xA proved to be the combination that worked best and in the anticipated way (a reduction of this load improved fuel economy).

ENGINE AND TRANSMISSION VARIATION - The 20 observations included seven pairs that used Atkinson cycle engines, which are used in the Toyota Prius and are more efficient than the base conventional vehicle engines used. The base engines in conventional vehicles varied in design. Theoretically, the most efficient of these was a gasoline direct injection (GDI) engine used by Weiss et al. in the MIT study (6). Weiss et al. also switched from an automated manual transmission in the base vehicle to a CVT in the hybrid. Based on mpg results for those CVTs that have been sold by Honda in the United States, including the Insight, a switch from a manual to a CVT reduces fuel economy. The efficiency of the CVT in Honda vehicles has been intermediate between the automatic and the manual, with a larger benefit for the CVT relative to the automatic in urban driving. The two “mild” hybrid cases of An, Santini and Stodolsky involve a switch from an automatic in the base vehicle to an automatic in the hybrid. The full hybrid cases involve a switch from an automatic to a CVT. In total, there are three cases in the sample in which a switch to a CVT has been made in the hybrid. Two of these are from an automatic in the base vehicle, and this should increase fuel economy. In the case of five Graham et al (2) switches, each switch is from automatic to manual. This also should improve fuel economy. An, Santini and Stodolsky provided estimates of the before and after transmission efficiency, by driving cycle. The estimates contradict the empirical information from Honda, with greater gains on the highway cycle than the city cycle. Only the Wiess et al. CVT switch is from a manual, and this should reduce efficiency, as is observed in the Insight. In the Insight, the city-cycle mpg drops 7% when a CVT is substituted for the manual, while the highway-cycle mpg drops by 18%. According to Honda, some of these fuel economy reductions may be attributable to the different engine combustion systems (lean-burn in the manual). For comparison, we do note that the 1997 Honda Civic CVT which had the same VTEC-E engine as an available manual transmission model also exhibited the property of a larger fuel economy drop of on the highway cycle (14%) than on the city cycle (8%) (15). No similar comparison is possible in the Weiss et al. study.

HYBRID CITY MPG VS. HIGHWAY MPG RELATIONSHIPS - The three simulated CVT hybrid pairs can be compared to the Prius and Insight CVTs in terms of the relationship between simulated city and highway mpg. The average ratio of city to highway mpg for the Prius and Insight is 0.94. The ratio for the two CVT cases constructed by An, Santini and Stodolsky is 1.04, while the ratio for the Weiss et al. case is 0.74. Ironically, for this statistic, the two highest values in the sample are for the An, Santini and Stodolsky hybrids with CVTs, and the lowest value is for the Weiss et al. hybrid CVT. The other studies did not simulate a CVT because there was no component model of a CVT in the ADVISOR model. For the remaining 17 comparisons, based on manual and automated manual transmissions, the mean ratio of hybrid city to highway mpg is 0.84, while the ratio for the Insight with a manual transmission is 0.88, which is within one standard deviation of the mean. In other words, there is no statistically significant difference between the city/highway mpg ratio for the manual transmission Insight and the mean of the ratio from the manual transmission hybrids in this sample. The ratio of hybrid city to highway mpg for the GM pickup truck simulation, based on an automatic transmission (13), was 0.98. As of the date of completion of these studies, CVT modeling seems to be a study area in need of attention. The Graham et al. study lamented the inability to simulate a CVT.

COMPLEX REGRESSION MODEL TESTS - Raw data used to estimate values used in the regression results presented below are included in Appendix A. There were 20 CV/HEV pairs. Six of the 20 are grid connectable, and have some all-electric range. Fourteen are like the Prius and Insight — designed only to run on gasoline. Regression models for the full sample of 20, and the subset of 14 were constructed, and numerous experiments were completed. The regression models estimated here are in the logarithmic form. The dependent variable is the natural log of fractional change in mpg fuel economy [Ln(g)], for the city, COMP, or highway cycle. The fuel economy ratings used and included in Appendix A are the unadjusted values (official EPA test values), although it would not make any difference to this analysis, given the construction of the dependent variable in the regressions.

VEHICLE ATTRIBUTES VS. SIMULATION MODELS AS CAUSES OF VARIATION IN PREDICTED MPG GAINS - Note that the correlation coefficient for Ln(t) and Ln(k) is 0.97. The correlation of Ln(e) and Ln(m) is also 0.97. Thus, these variables are essentially surrogates for one another in this sample. Knowing this, one can compare the explanatory power of the simple two-variable model in Table 2 to the five-variable model in Table 3. By adding the three variables on motor size when motors have more peak kW than engines (Ln(m) if m >1), the product of frontal area and coefficient of drag ln($C_d$xA), and the use of Atkinson cycle engines in hybrids (a), the coefficient of determination ($R^2$) in the composite regression rises only from about 0.86 to 0.92. When we

add dummy variables to allow for the possibility of unexplained variation among the studies examined, the coefficient of determination in the full sample composite regression rises from 0.92 to 0.99. We have suggested a partial explanation for the lower value from the Weiss et al. study: the unique transmission switch from the conventional vehicle to the hybrid. Similarly, we noted that the transmission switch in the five Graham et al (2) cases should improve fuel economy. Thus, more than 92 % of the composite cycle variation among the studies is explainable through technical information about the inputs to the models used. Remaining variation among the studies is estimated to be less than 7%.

The results are not so dramatic in the case of the city and highway regressions, suggesting some compensating errors in the composite results. Nevertheless, it is clear that if one can understand the design goals for hybrid and conventional vehicles that are to be compared to one another, the level of uncertainty in estimating gains in fuel economy is dramatically reduced. This uncertainty is *far* less than that implied by taking the standard deviation about the 20-observation sample mean or about a 21-sample mean if we include the GM study. The earlier discussion of ranges of uncertainty in the Weiss et al. and GM studies suggests that the posited uncertainty bands are too wide for an individual vehicle pair "designed" under well-defined performance constraints. Because these two studies, and the GREET full fuel-cycle model used in both of them make pairwise comparisons of conventional and advanced vehicles, the degree of uncertainty inherent in the estimates is a significant issue. At present, the uncertainty bands suggested for GREET are related to the spread of values found in various studies (16). The method used to determine vehicle input to date has been to choose a mean or median value from a sample of studies in the literature. Performance capabilities of the vehicles have not been considered as a possible determinant of appropriate fuel economy predictions to enter into the model.

VARIATION AMONG STUDIES - In preliminary experiments, we found that the An, Stodolsky, and Santini and the Graham et al. studies (represented by dummy variables F and G) were, with only one exception in six regression tests for models in Tables 3 and 4, not significantly different from one another. In effect, both have almost identical coefficients relative to the Plotkin et al. study, which is used as the reference point (since it has the largest number of pairs in the sample). They are also significantly more optimistic than the Plotkin et al. study. The An, Stodolsky, and Santini study uses a different vehicle simulation model than the Plotkin et al. study, so the difference may well be attributable to the different models used. Both the Graham et al. study and the Plotkin et al. study use the same vehicle simulation model, ADVISOR. However, despite the publication dates of the two reports, the actual modeling runs for the Plotkin et al. study were conducted earlier than those for the Graham et al. study. Component efficiencies and capabilities were improving over that time period, and the Graham et al. study used higher-performance components — especially batteries — than the Plotkin et al. study. The one case of the Weiss et al. study is clearly an outlier in this study, but with a logical explanation.

DIMINISHING RETURNS TO BATTERY PACK AND MOTOR SIZE - The coefficient for the variable Ln(m) if m >1 is not statistically significant until the unexplained variation among the studies is estimated through dummy variables. The negative sign of the coefficient is consistent with the expectation that, as far as gasoline-only fuel economy is concerned, there may be limits to the benefits of reducing engine size and increasing motor and battery pack size.

EFFECTS OF REDUCING AERODYNAMIC DRAG - Coefficients for the "drag area" variable [$\ln(C_d x A)$] implied that reduction of drag improves the fuel economy benefits of hybridization significantly on the highway driving cycle. If any effect were found, the physics involved make it far more likely that the effect would occur on the highway cycle. When the unexplained variation among studies was accounted for by use of dummy variables, the coefficients and t-values for the drag area variable increased dramatically, were consistent in sign, and were consistently estimated to be statistically significant across all three driving cycles. Coefficients increased in magnitude as we moved from city to composite to the highway driving cycle, consistent with the physics involved. Because the coefficients were unstable, more research should be conducted with larger sample sizes before making use of the estimated coefficients. The results suggest that some effort should be devoted to examining the physics and engineering involved. We suggest that the reduction of drag area for a given mass and motor/battery pack size enhances the recovery of energy through regenerative braking by reducing losses to heat the air. We cannot reliably determine the degree to which this is true based on the results of these regression models.

ATKINSON CYCLE ENGINES - Regression model results support the expectation that installation of more efficient Atkinson cycle engines in hybrids (these engines are not suitable for conventional vehicles) increases fuel economy. Coefficients obtained are stable for the city and composite regressions, but unstable for the highway regression.

Table 3 Complex Full Sample Regression Models of Fuel Economy Change

| | City Cycle Base Model | City Cycle Studies Model | COMP Cycle Base Model | COMP Cycle Studies Model | Highway Cycle Base Model | Highwa y Cycle Studies Model |
|---|---|---|---|---|---|---|
| Constant | 1.87 (3.20) [3] | 1.62 (5.16) [3] | 2.06 (3.87) [3] | 1.59 (6.40) [3] | 2.50 (1.34) | 0.55 (0.43) |
| Ln(k) | 0.87 (4.24) [3] | 1.07 (9.54) [3] | 1.15 (6.17) [3] | 1.25 (14.12) [3] | 2.21 (3.37) [3] | 1.69 (3.70) [3] |
| Ln(m) | 0.28 (2.80) [2] | 0.34 (6.00) [3] | 0.37 (4.10) [3] | 0.41 (9.13) [3] | 0.98 (3.05) [3] | 0.66 (2.83) [2] |
| Ln(m) if >1 | -0.22 (-0.87) | -0.47 (-3.40) [3] | -0.31 (-1.36) | -0.52 (-4.71) [3] | -0.87 (-1.08) | -0.40 (-0.70) |
| Ln(Cd x A) | -0.11 (-0.32) | -1.40 (-5.38) [3] | -0.66 (-2.16) [2] | -1.91 (-9.26) [3] | -3.70 (-3.44) [3] | -4.74 (-4.46) [3] |
| a | 0.28 (2.74) [2] | 0.17 (2.21) [2] | 0.20 (2.10) [2] | 0.18 (2.86) [3] | 0.03 (0.11) | 1.05 (3.26) [3] |
| F+G | | 0.37 (4.56) [3] | | 0.24 (3.72) [3] | | -1.09 (-3.27) [3] |
| S | | -0.12 (-1.37) | | -0.28 (-3.93) [3] | | -1.09 (-2.99) [3] |
| W | | -0.65 (-5.68) [3] | | -0.66 (-7.19) [3] | | -1.07 (-2.28) [2] |
| $R^2$ | 0.87 | 0.97 | 0.92 | 0.99 | 0.86 | 0.96 |
| F-Stat | (18.1) [3] | (51.5) [3] | (33.5) [3] | (119) [3] | (17.2) [3] | (29.7) [3] |

Notes: t-values in parentheses; t-value superscript 1 indicates prob>t <0.10, 2 indicates <0.05, 3 indicates < .01. Number of observations = 20

Table 4 Complex Part Sample Regression Models of Fuel Economy Change (grid-connectable HEVs deleted)

| | City Cycle Base | City Cycle Studies | COMP Cycle Base | COMP Cycle Studies | Highway Cycle Base | Highway Cycle Studies |
|---|---|---|---|---|---|---|
| Constant | 2.07 (3.04) [3] | 1.34 (3.75) [3] | 2.14 (3.12) [3] | 1.09 (3.03) [2] | 1.72 (0.64) | -1.88 (-1.97) [1] |
| Ln(k) | 0.90 (4.10) [3] | 1.03 (9.46) [3] | 1.16 (5.27) [3] | 1.20 (11.38) [3] | 2.11 (2.44) [2] | 1.51 (5.37) [2] |
| Ln(m) | 0.27 (2.86) [2] | 0.29 (6.01) [3] | 0.34 (3.63) [3] | 0.33 (7.52) [3] | 0.84 (2.30) [2] | 0.50 (4.07) [3] |
| Ln(Cd x A) | 0.15 (0.39) | -1.49 (-4.14) [3] | -0.51 (-1.26) | -2.38 (-6.83) [3] | -4.26 (-2.70) [2] | -7.76 (-8.39) [3] |
| a | 0.32 (2.57) [2] | 0.27 (3.47) [3] | 0.23 (1.84) [1] | 0.29 (3.86) [3] | 0.11 (0.23) | 1.24 (6.28) [3] |
| F+G | | 0.38 (4.75) [3] | | 0.25 (3.32) [3] | | -0.95 (-4.66) [3] |
| S | | -0.09 (-1.00) | | -0.30 (-3.44) [3] | | -1.47 (-6.39) [3] |
| W | | -0.64 (-4.76) [3] | | -0.77 (-5.91) [3] | | -2.02 (-5.84) [3] |
| $R^2$ | 0.86 | 0.98 | 0.91 | 0.99 | 0.82 | 0.99 |
| F-Stat | (14.2) [3] | (42.8) [3] | (20.8) [3] | (65.6) [3] | (10.1) [3] | (76.2) [3] |

Notes: t-values in parentheses; t-value superscript 1 indicates prob>t <0.10, 2 indicates <0.05, 3 indicates < .01. Number of observations = 14

HIGHWAY VS. OTHER CYCLE RESULTS - The highway-cycle coefficient estimates are the least stable and the least reliable. Because the composite cycle results were obtained by using a composite measure of fuel economy combining the city and highway cycle, but with considerably more weight for the city cycle (55% of gpm vs. 45% for highway), it is not surprising that the results for the composite cycle are stable. Despite the uncertainty in the highway-cycle results, those results are also less important in determining the composite fuel economy gain because average gains in fuel economy are considerably greater on the city cycle (sample mean = 67.4%) than the highway cycle (sample mean = 24.7%). So, greater uncertainty on the highway cycle is not particularly troublesome because it relates to a very small part of the composite effect.

## SUMMARY OF RESULTS

Clearly, over the wide range of k (peak kW/kg) values used in this study, there is a strong increase in potential mpg gain via hybridization as power-to-weight ratio increases. As the power-to-weight ratio increases by 10%, the potential to improve mpg increases by about the same amount. Increasing the motor size relative to the engine size appears to provide fuel economy benefits. This occurs in lock step with engine size reduction under the rules of comparison adopted in this study. The inconclusive results for the Ln(m) if m >1 variable before and after the inclusion of dummy variables (to allow for variation among studies) suggest that diminishing returns to battery pack and motor size must be considered. However, because of motor and battery pack costs, this issue is probably not particularly important; hybrids with motor kW in excess of engine kW are not likely to be built by major automobile manufacturers. For the driving cycles simulated, as the power of the motor increases, the ability to recapture braking energy improves. However, at some point — here estimated to be when the motor kW is equal to the engine kW — there is no additional benefit. An, Santini, and Stodolsky illustrate how, at some point related to the nature of the driving cycle and the motor/battery power, all braking energy available is recoverable and more motor and battery pack provides no value with regard to energy recovery. Past that point, its primary effect is likely to be to add mass, and therefore reduce fuel economy. Up to that point, the estimates here imply that at every 10% increase in the value of m results in an increase of 3%–4% in mpg gain for the city and composite cycles. For the highway cycle, the estimates imply that the effect of added motor size — or greater engine size reduction, or both — provides an even larger contribution to improving fuel economy.

As discussed earlier, it appears that load reduction improves the percentage gain in mpg that is possible. The statistical results support the physics for “drag area” ($C_d$xA), which say that a more efficient engine will improve fuel economy. In this case, the engine is an Atkinson cycle engine, which does not have adequate specific power for use in a conventional vehicle. For the limited information on transmission switches, the results are consistent with a loss of fuel economy when switching from a manual to a CVT (the coefficient value of one observation is compromised by the fact that it uses a different vehicle simulation model).

## CONCLUSIONS

This study estimates that the variability in published estimates of fuel economy gains when switching from a conventional to a hybrid powertrain in an otherwise identical vehicle body can largely be explained if one knows the key vehicle attributes for the compared vehicles. In particular, knowing the 0–60 mph acceleration time, vehicle mass, peak conventional vehicle powertrain kW, and peak engine and motor kW of the hybrid vehicle allows researchers to explain more than 80% of the variation among studies. Not all of these items are necessary. On the basis of the models developed and presented here, or simple extensions of them, researchers can construct estimates of fuel economy improvement by using the following four combinations: (1) kW/kg (variable k) and percent engine power reduction in the conventional to hybrid switch (e), (2) kW/kg (k) and peak motor power to peak engine power ratio in the hybrid (m), (3) 0-60 mph acceleration time (t) and percent engine power reduction in the conventional to hybrid switch (e), and (4) 0-60 mph acceleration time (t) and peak motor power to peak engine power ratio in the hybrid (m). Options 2 and 3 have been done here (Tables 2-4). Options 1 and 4 may be done by use of the database in Appendix A.

Within the range of values included in the study, $C_d$xA, engine type (if engine efficiency is much different), and transmission switches are estimated to make a difference, but only add a few percent points to the statistical explanation ($R^2$) of variation in percent gains in fuel economy. Unexplained variation caused by unknown study details and/or different vehicle simulation methods represents only a small percentage of the unexplained $R^2$ after the previously discussed variables have been included in the regressions. The (absence of positive) results are consistent with an interpretation that when tire rolling resistance ($C_r$) is the same for both the hybrid and conventional vehicle, there is no influence on the percentage difference in fuel economy between the two vehicles. This is hardly a definitive result.

The statistical results should be regarded as a tool to help summarize results across studies. In light of the small sample size and the likelihood of correlated errors, the estimates of statistical significance are uncertain. Only a few of the technical options for hybridization have been included in the studies surveyed. In many cases, there is not enough information to evaluate the effects of individual components. Nevertheless, the results provide a guide, and the data collected provide consistent

reference points from which additional analyses can be developed.

For example, on the basis of the data used in other studies, analysts could construct vehicle simulations consistent with regard to input data used in studies other than their own, and enrich the database provided here. With a larger database and more experiments, statisticians can investigate the relationships among errors and develop more reliable coefficient estimates. For the part of vehicle simulators, some hypotheses can be evaluated by more careful parsing of vehicle simulation results so that the tradeoffs suggested here can be confirmed, refuted, and/or refined.

## ACKNOWLEDGMENTS

DOE's Office of Transportation Technologies (OTT) provided funding for preparation of this paper. We thank our external reviewers, Norm Brinkman and Trudy Weber of General Motors, David Hermance of Toyota, and Benjamin Knight of Honda. Theirs and SAE reviewers' constructive comments made this a better paper. However, the authors are solely responsible for its contents.

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## DEFINITIONS ACRONYMS AND ABBREVIATIONS

ACRONYMS

| | |
|---|---|
| ADVISOR | Advanced Vehicle Simulator |
| CARB | California Air Resources Board |
| COMP | Composite city and highway fuel economy based on 55/45 split |
| Cd | coefficient of drag |
| Cr | rolling resistance |
| CVT | continuously variable transmission |
| DOE | U.S. Department of Energy |
| EPRI | Electric Power Research Institute |
| FHV | Full Hybrid Vehicle |
| FTP | Federal Test Procedure |
| GDI | gasoline direct injection |
| GM | General Motors Corporation |
| MHV | Mild Hybrid Vehicle |
| NREL | National Renewable Energy Laboratory |

UNITS OF MEASURE

| | |
|---|---|
| gal | gallon(s) |
| gpm | gallon(s) per mile |
| kg | kilogram(s) |
| kW | kilowatt(s) |
| $m^2$ | square meter(s) |
| mi | mile(s) |
| mpg | mile(s) per gallon |
| mph | mile(s) per hour |
| rpm | revolutions per minute |

## APPENDIX A

Table A1 Characteristics of Conventional and Hybrid Vehicles Analyzed

| Ref | EV Miles | 0-60 (sec) | CV City mpg | HEV City mpg | CV Hwy mpg | HEV Hwy mpg | CV kg | CV kW | HEV kg | HEV ICE kW | HEV motor kW | Trans-missions | Atkin-son | Cd | A | Cr | HEV top speed | HEV grade % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 0 | 14 | 34.8 | 47.6 | 49.8 | 50.5 | 1304 | 55 | 1406 | 45 | 15 | a,a | 0 | .30 | 2.00 | .0090 | na | na |
| 5 | 0 | 14 | 34.8 | 49.7 | 49.8 | 51.5 | 1304 | 55 | 1512 | 43 | 21 | a,c | 1 | .30 | 2.20 | .0070 | na | na |
| 4 | 0 | 12 | 33.2 | 49.5 | 56.1 | 62.1 | 1181 | 67 | 1215 | 42 | 25 | m,m | 0 | .24 | 2.00 | .0065 | na | 6.5 |
| 3 | 0 | 12 | 32.2 | 42.7 | 47.1 | 52.4 | 1175 | 66 | 1246 | 55 | 14 | m,m | 0 | .26 | 2.06 | .0075 | na | 9.0 |
| 3 | 0 | 12 | 32.2 | 46.7 | 47.1 | 57.0 | 1175 | 66 | 1247 | 44 | 25 | m,m | 0 | .26 | 2.06 | .0075 | na | 6.6 |
| 5 | 0 | 11 | 29.4 | 42.6 | 44.8 | 45.9 | 1304 | 85 | 1406 | 76 | 15 | a,a | 0 | .30 | 2.00 | .0090 | na | na |
| 5 | 0 | 11 | 29.4 | 51.1 | 44.8 | 46.6 | 1304 | 85 | 1542 | 70 | 30 | a,c | 1 | .30 | 2.20 | .0070 | na | na |
| 3 | 0 | 10 | 27.7 | 41.3 | 41.6 | 50.4 | 1248 | 85 | 1321 | 65 | 22 | m,m | 0 | .26 | 2.06 | .0075 | na | 10.7 |
| 3 | 0 | 10 | 27.7 | 45.2 | 41.6 | 55.7 | 1248 | 85 | 1328 | 46 | 43 | m,m | 0 | .26 | 2.06 | .0075 | na | 6.7 |
| 2 | 0 | 9 | 27.7 | 58 | 50.5 | 69.7 | 1408 | 98 | 1392 | 55 | 40 | a,m | 1 | .25 | 2.17 | .0055 | na | >7.1* |
| 2 | 0 | 9 | 23.2 | 40.6 | 41.4 | 43.7 | 1682 | 127 | 1603 | 67 | 44 | a,m | 1 | .33 | 2.17 | .0080 | 120 | >7.1* |
| 6 | 0 | 8.5 | 42.4 | 62.7 | 60.8 | 84.2 | 1136 | 85.2 | 1154 | 57.7 | 28.8 | m,c | 0 | .22 | 1.80 | 0.006 | na | na |
| 3 | 0 | 8 | 22.6 | 37.9 | 35 | 47.2 | 1366 | 116 | 1453 | 82 | 39 | m,m | 0 | .26 | 2.06 | .0075 | na | 13.2 |
| 3 | 0 | 8 | 22.6 | 42.5 | 35 | 52.8 | 1366 | 116 | 1466 | 49 | 75 | m,m | 0 | .26 | 2.06 | .0075 | na | 6.8 |
| 2 | 21 | 9 | 23.2 | 40.9 | 41.4 | 47.1 | 1682 | 127 | 1651 | 61 | 51 | a,m | 1 | .33 | 2.17 | .0080 | 98 | >7.1* |
| 3 | 23 | 8 | 22.6 | 43.3 | 35 | 53.8 | 1366 | 116 | 1439 | 48 | 54 | m,m | 0 | .26 | 2.06 | .0075 | na | 6.7 |
| 3 | 27 | 8 | 22.6 | 42.2 | 35 | 52.8 | 1366 | 116 | 1491 | 49 | 64 | m,m | 0 | .26 | 2.06 | .0075 | na | 6.7 |
| 3 | 33 | 8 | 22.6 | 41 | 35 | 51.5 | 1366 | 116 | 1566 | 50 | 78 | m,m | 0 | .26 | 2.06 | .0075 | na | 6.6 |
| 2 | 60 | 9 | 23.2 | 42.4 | 41.4 | 49.7 | 1682 | 127 | 1767 | 38 | 75 | a,m | 1 | .33 | 2.17 | .0080 | 97 | >7.1* |
| 2 | 60 | 9 | 27.7 | 56.3 | 50.5 | 67.3 | 1408 | 98 | 1531 | 34 | 65 | a,m | 1 | .25 | 2.17 | .0055 | na | >7.1* |
| 14 | 7.5 | 8&6 | 17.4 | 23.8 | 20.2 | 24.4 | na | na | na | na | na | a,a | 0 | na | na | na | 110 | >5.9# |

Notes: * Design minimum was 7.2% at 50 mph for 15 minutes.
# Design minimum was 6% at 55 mph for 20 minutes.
na = not available.