A New Composite Drive Cycle for the Evaluation and Test of Heavy Duty Hybrid Electric Class 4-6 Urban Delivery Vehicles

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Diesel Engine Emissions Part 2: Powertrain Analysis and Duty Cycle Simulation

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Presentation Overview

- Background on the DOE AHHPS Program & Eaton Team
- Drive Cycle Considerations
  - Why we did this work
  - Types of Drive Cycles
  - Cycle Selection Criterion
- Methodology and Cycle Selection Process
- Summary

Background on the AHHPS Program

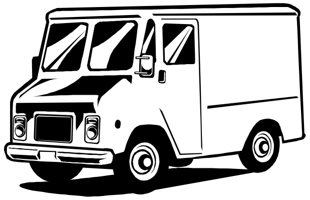
- **A**dvanced **H**eavy **H**ybrid **P**ropulsion **S**ystem Program:
  - a cost-shared R&D program between the US Department of Energy, NREL, and Competitively Selected Industry Teams
  - Currently 3 teams awarded
- AHHPS program Goals:
  - Increase the fuel efficiency of heavy trucks (Class 3-8) and buses by as much as 100% (2x) over baseline.
  - Reduce U.S. dependence on foreign oil
  - Maintain future Environmental Protection Agency emissions standards
- the program is in two phases:
  - phase I: technology development
  - phase II: technology demonstration

appropriate duty cycle will need to be chosen by each team

Advanced Heavy Hybrid Propulsion Systems

Background on the Eaton Team

- Team Members:
  - Eaton Corporation
  - International Truck and Engine Corporation
  - Ricardo
- Subcontract awarded September 2002
- Class 4-6 hybrid truck application
  - Focus on Urban Pickup and Delivery Application
  - Parallel Hybrid System



Considerations for the Drive Cycle

Why we did this work:

- to benchmark fuel economy and emissions in context of AHHPS program
- the duty cycle will affect the fuel economy of any vehicle
- HEV fuel economy and HEV benefit are directly tied to the drive cycle

Why we used existing cycles to create our cycle:

- detailed information from delivery fleets considered proprietary
- there are many good cycles available--wish to fit those cycles to our application
- stock cycles have wide degree of use; accepted in the engineering community

Messages to take home:

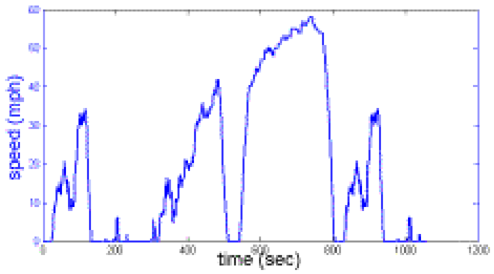
- **DRIVE CYCLE DOES MATTER!**
- our cycle is a good choice among several reasonable choices
- it is the best fit to the data we have from the target customer
- this cycle is **not** proposed as a new standard
- we are highlighting the methodology over the final result

Contrasting the Cycle Types

Element, Composite, and Weighted Cycles

Element Cycles:

UDDS-Schedule D



The speed-time trace as obtained from literature and standards

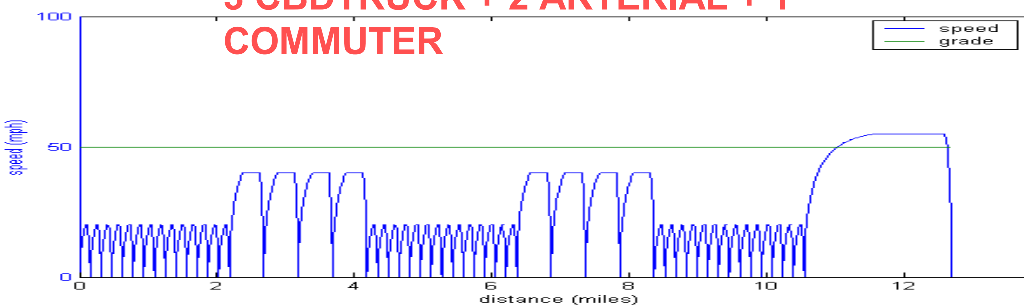
Weighted:

$$\text{Fuel Economy} = \frac{1\,\text{mile}}{\left(\frac{0.55\,\text{mile}}{MPG_{CITY}} + \frac{0.28\,\text{mile}}{MPG_{SURB}} + \frac{0.17\,\text{mile}}{MPG_{HWY}}\right)}$$

Combines several cycles without losing per-cycle information

Composite:

3 CBDTRUCK + 2 ARTERIAL + 1 COMMUTER



Combines various types of driving into one cycle

Drive Cycle Criterion for our Application

1st
1. suitable for both fuel economy and emissions testing (suitable test cycles)

2nd
2. cycle must be acceptable to all parties involved (acceptable)

3rd
3. traction power appropriate to vocation (meet trace)

4th
4. representative of actual customer driving patterns in vocations applicable to HEVs (representative driving)

5th
5. ease energy storage State-of-Charge (SOC) correction (ease SOC correct)

6th
6. easy to execute in both dynamometer and field testing (ease of execution)

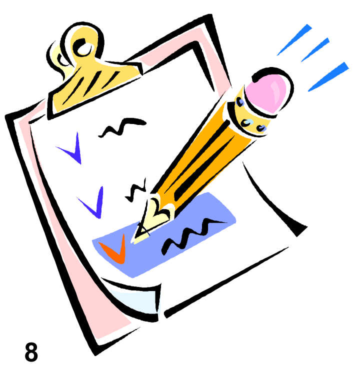
Criterion Data for our Application

Baseline Vehicle:(target application)

- Max Engine Power: 175 hp (130 kW)
- examined GVW: 23440 lbs. and half payload weight

Metrics from the Customer

- miles between stops: ~ 0.59 (note:all stops)
- average speed : ~ 17.6 mph
- City/Sub./Hwy: 55% / 28% / 17%



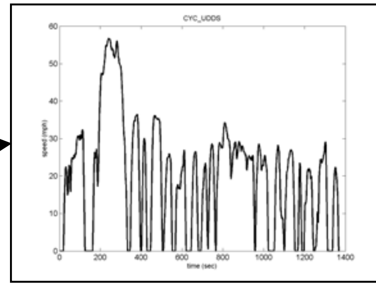
Note: this information represents the target customer’s knowledge of the duty cycle

The Drive Cycle Selection Process

A Process of Elimination

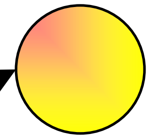
1. Cycle Library

a collection of all candidate drive cycles



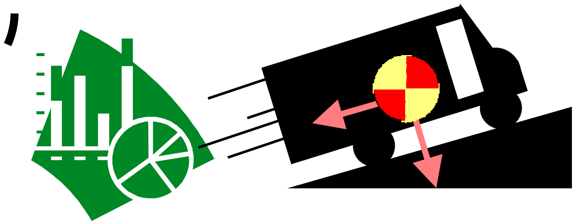
2. Drive Cycle Trace

the speed versus time information of the cycle



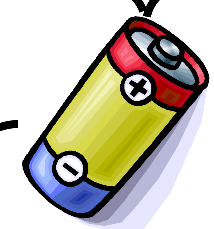
3.1 Combine/Weight Cycles

weighted and composite cycles created



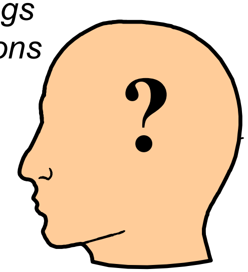
3.2 Trace Statistics and Simple Vehicle Kinetics

speed and acceleration histograms and averages; maximum tractive forces required



4. Ease of SOC Balancing

The fuel energy used over a cycle must be large compared with the change in State-of-Charge of the Hybrid Energy Storage System.

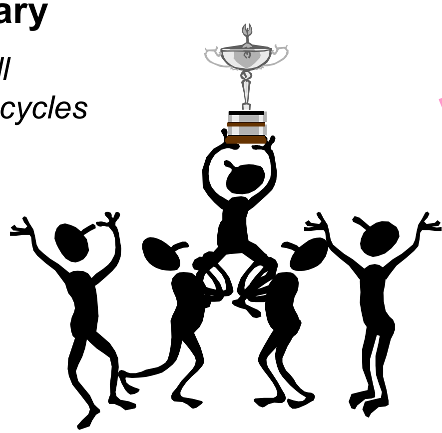


5. Meet Criterion?

check how cycle compares to customer driving patterns and available vehicle performance

6. If not, Feedback?

new weightings or combinations



Team Consensus

Down-select from the remaining cycles to a cycle everyone can agree upon.

Downselecting by Suitability and Group Acceptability

1st/ 2nd

CRITERION

acceptable & suitable test cycles

- Initial Cycles came from:
  - NREL's ADVISOR™ vehicle simulation software library
  - contributions by Eaton and International
- We only considered cycles
  - acceptable by the group
  - previously used to measure fuel economy and emissions
- This left us with ~50 cycles to examine

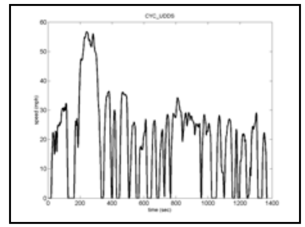
ADVISOR is a trademark of the Midwest Research Institute

3rd CRITERION

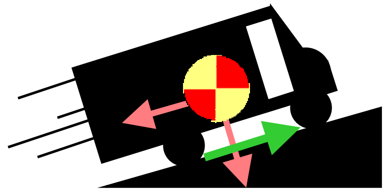
Down Selection of Element Cycles based on power requirement

meet trace

baseline vehicle characteristics (CD, FA, GVWR, rolling resistance, etc.) +

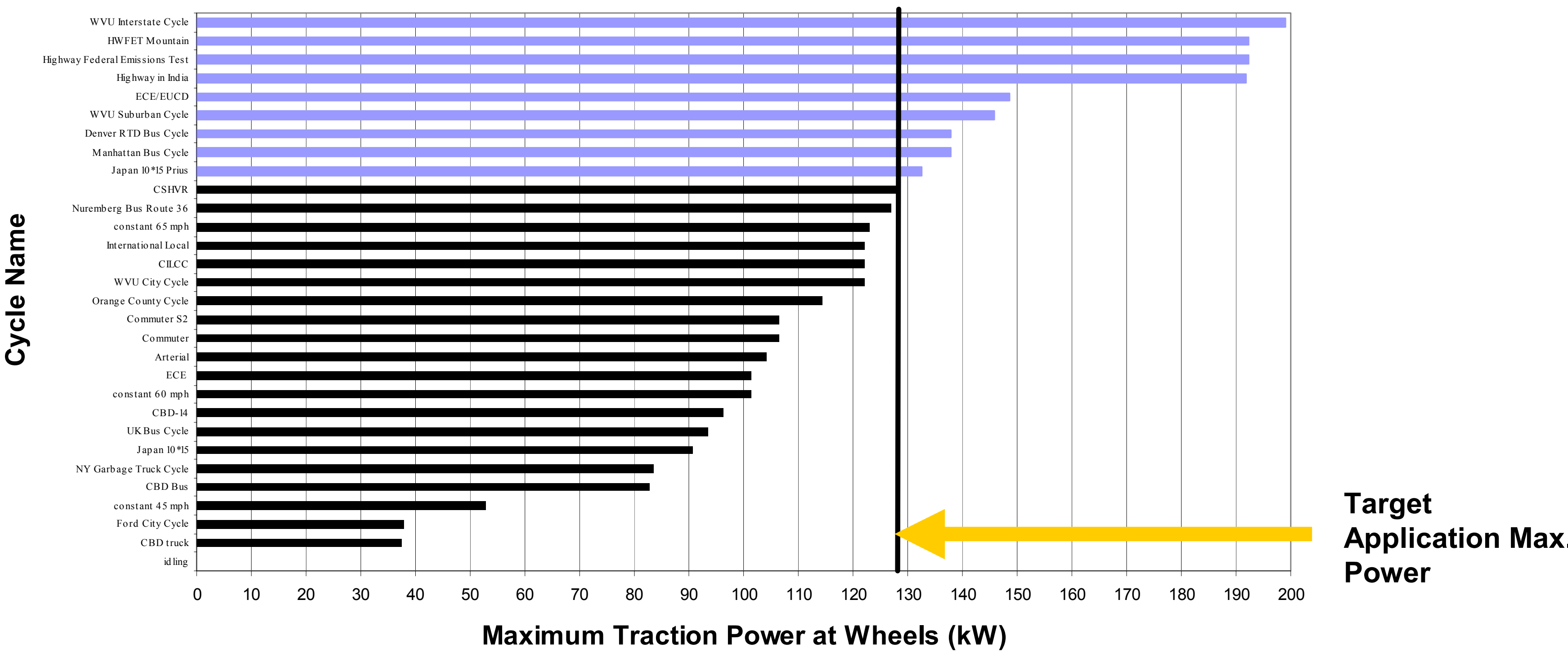


Cycle Trace =



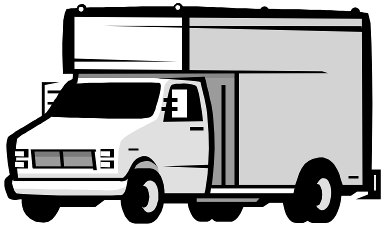
Vehicle Kinetic Calcs

Maximum Traction Power Required by Cycle



Weighted & Composite Cycles made from "Drivable" Element Cycles

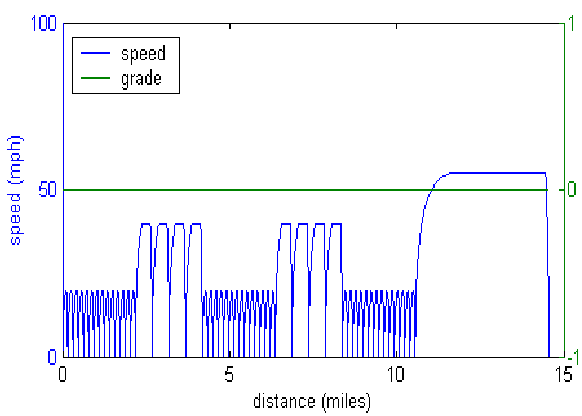
- ~20 element cycles can be driven by our baseline application
- However, these element cycles did not match target customer data to satisfaction
- Therefore, weighted cycles and composite cycles were considered

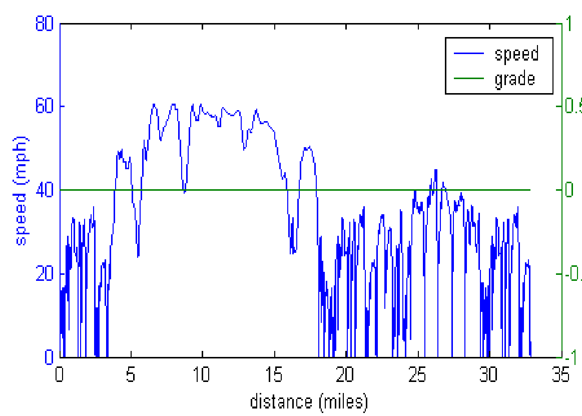


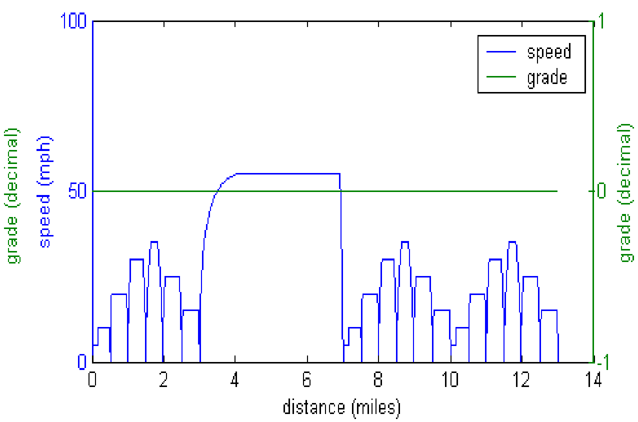
Example Composite Cycles

Cycle	Time (sec.)	Dist. (mile)	ASpd (mph)	# of Stops	Stop Time	City (%)	Sub (%)	Hwy (%)	MPG Gain
Composite 1 *	3466	14.6	15.11	51	613	45	27.5	27.5	32%
Composite 2**	7533	32.9	15.7	60	1854	30	22.7	47.3	39%
Composite 3***	2978	13	15.7	19	514	46	23	31	34.6%

* = 3 CBDTRUCK + 2 ARTERIAL +1 COMMUTER ۞
** = 3 WVUCITY + 1 WVUSURB + 1 WVUINTER
*** = 3 Int'l Local + 1 COMMUTER



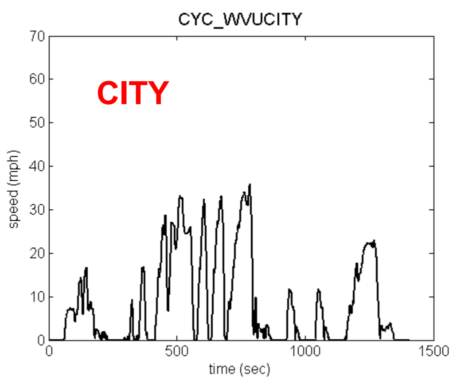


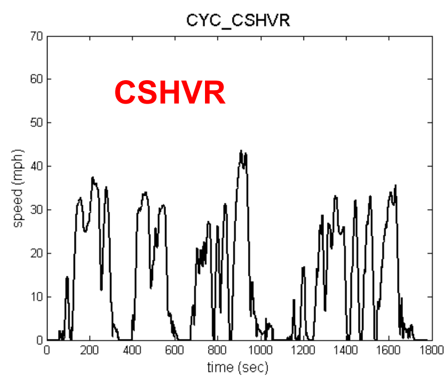


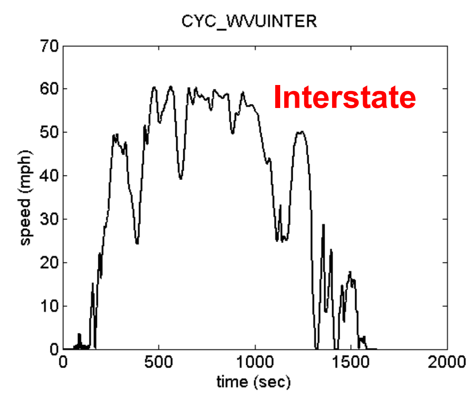
۞ *SAE J1376, cancelled 1997*

Example Weighted Cycle

- West Virginia University Cycles*:
  - City Cycle
  - City Suburban Heavy Vehicle Route (CSHVR)
  - Interstate Cycle

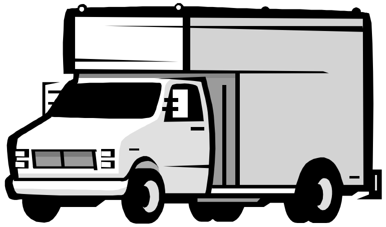






$$\text{Fuel Economy} = \frac{1\,\text{mile}}{\left(\frac{0.55\,\text{mile}}{MPG_{CITY}} + \frac{0.28\,\text{mile}}{MPG_{SURB}} + \frac{0.17\,\text{mile}}{MPG_{HWY}}\right)}$$

*ref SAE: 1999-01-1467

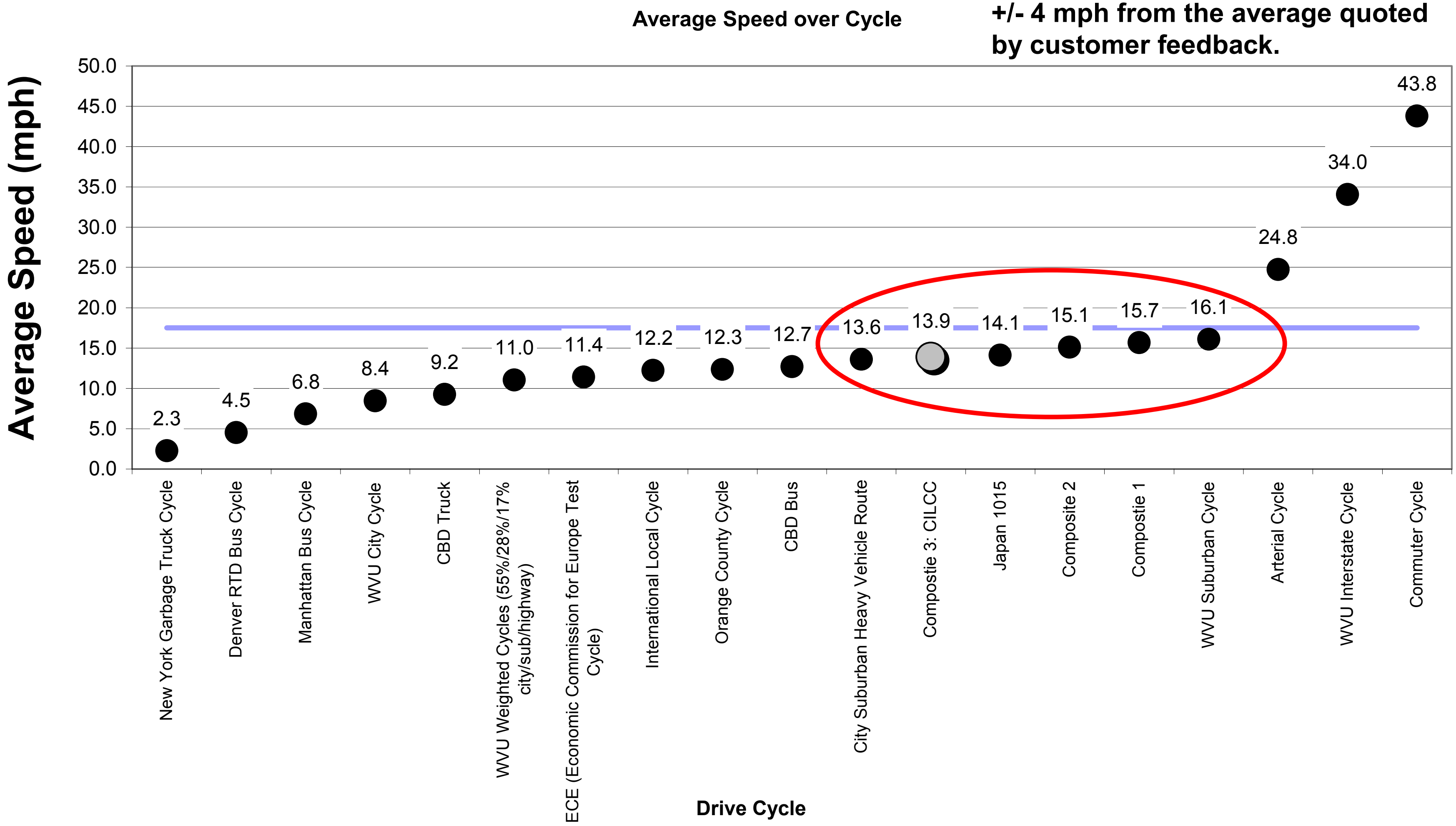


Using Customer Metrics for Further Down-Selection

4th CRITERION

representative driving

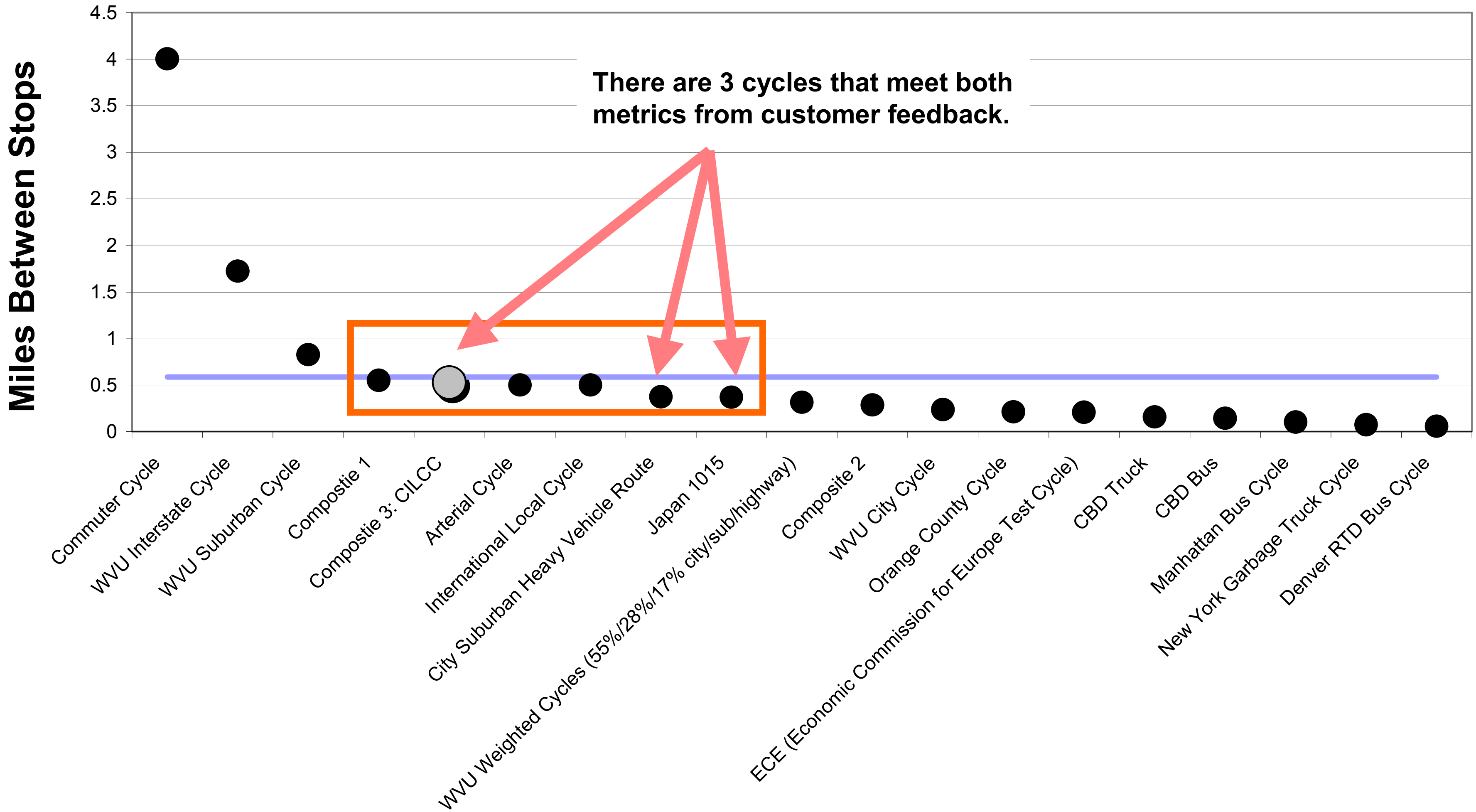
There are 6 cycles with speeds of +/- 4 mph from the average quoted by customer feedback.



Using Customer Metrics for Further Down-Selection

4th CRITERION

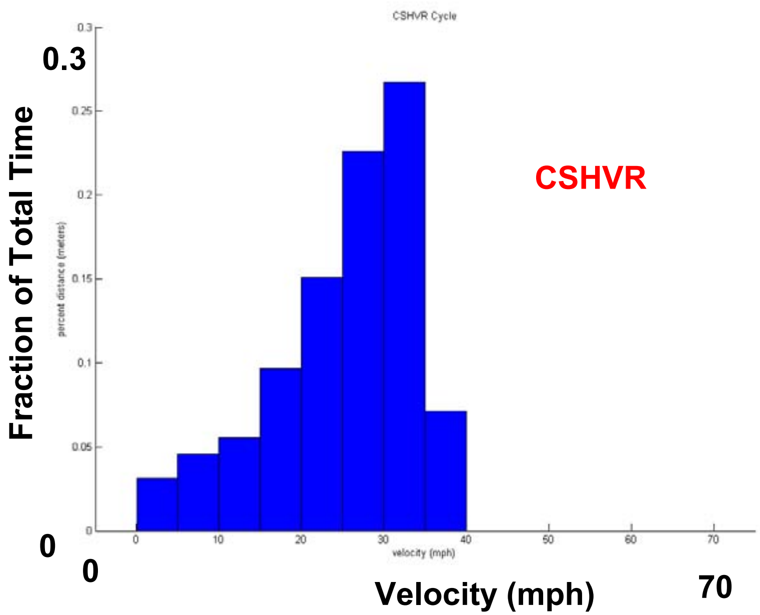
representative driving

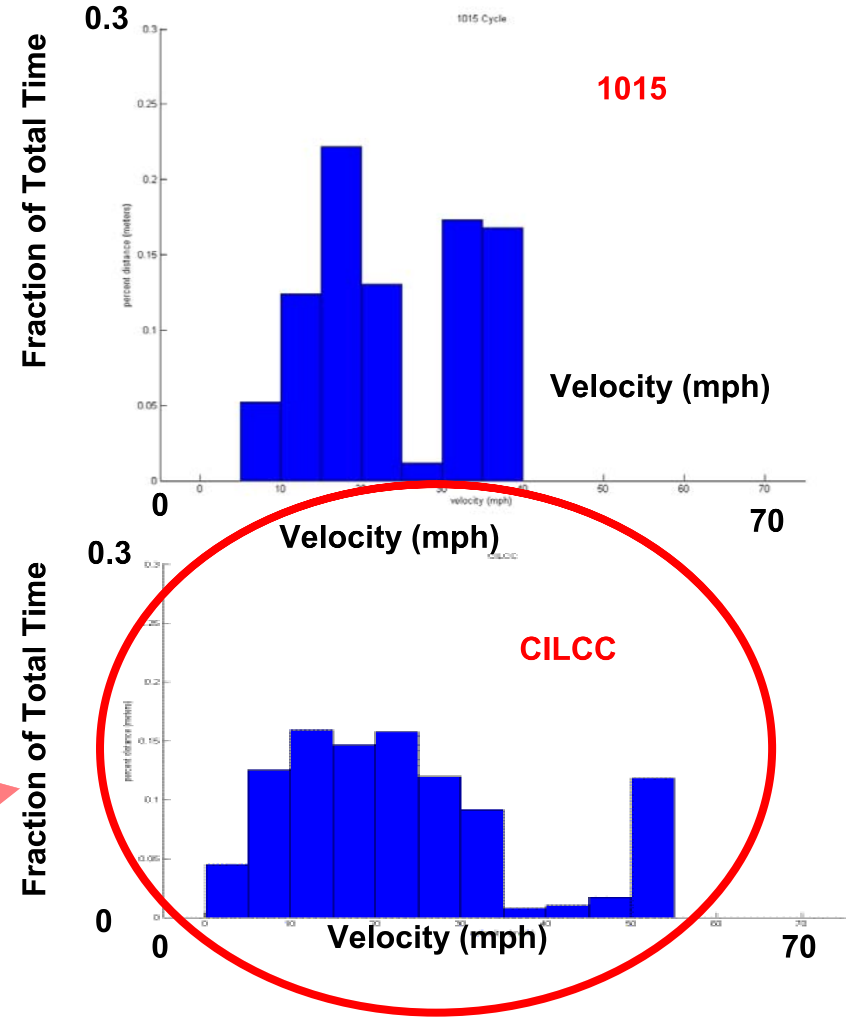


CRITERION

Looking at the Speed Distributions

representative driving





CILCC contains freeway speed driving.

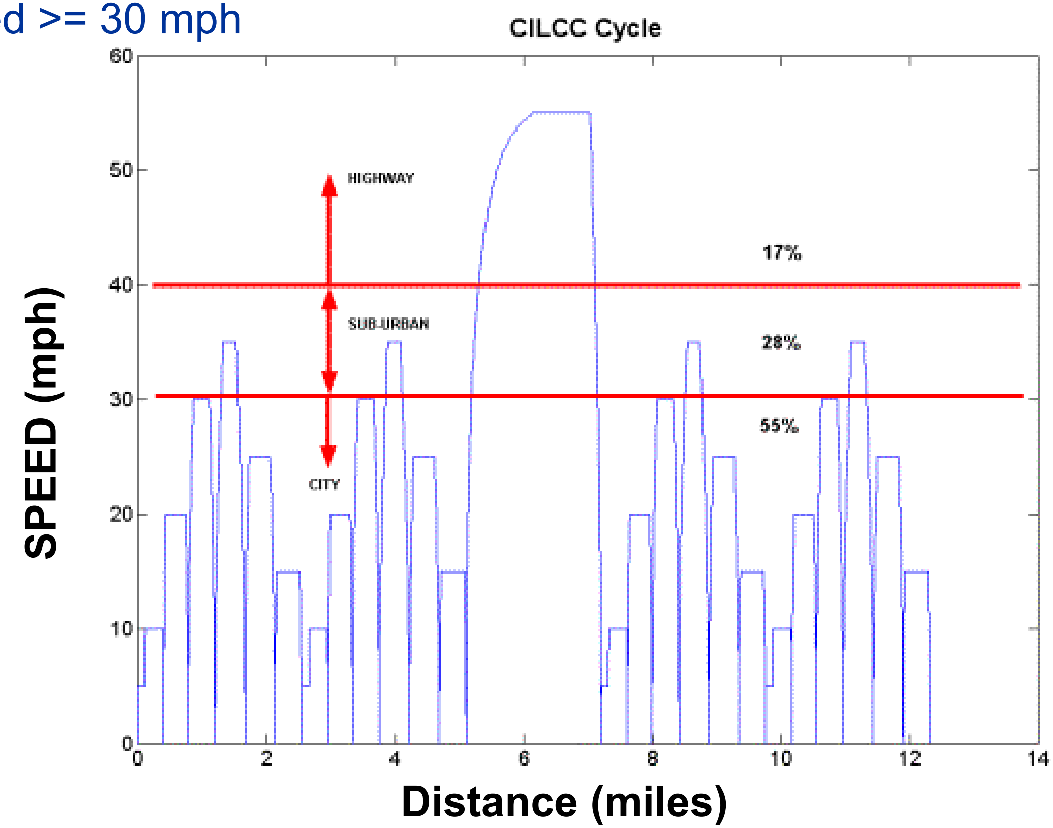
Examining Speed Distributions
Classifying City, Suburban, and Freeway Driving

Peak-Speed on Micro-trip
- microtrip = the travel profile between a start and stop
- the top speed is used to classify microtrips
- City: 30 mph > top speed > 0 mph
  Suburban: 40 mph >= top speed >= 30 mph
  Highway: top speed > 40 mph

The distribution from customer:

55% city
28% suburban
17% highway

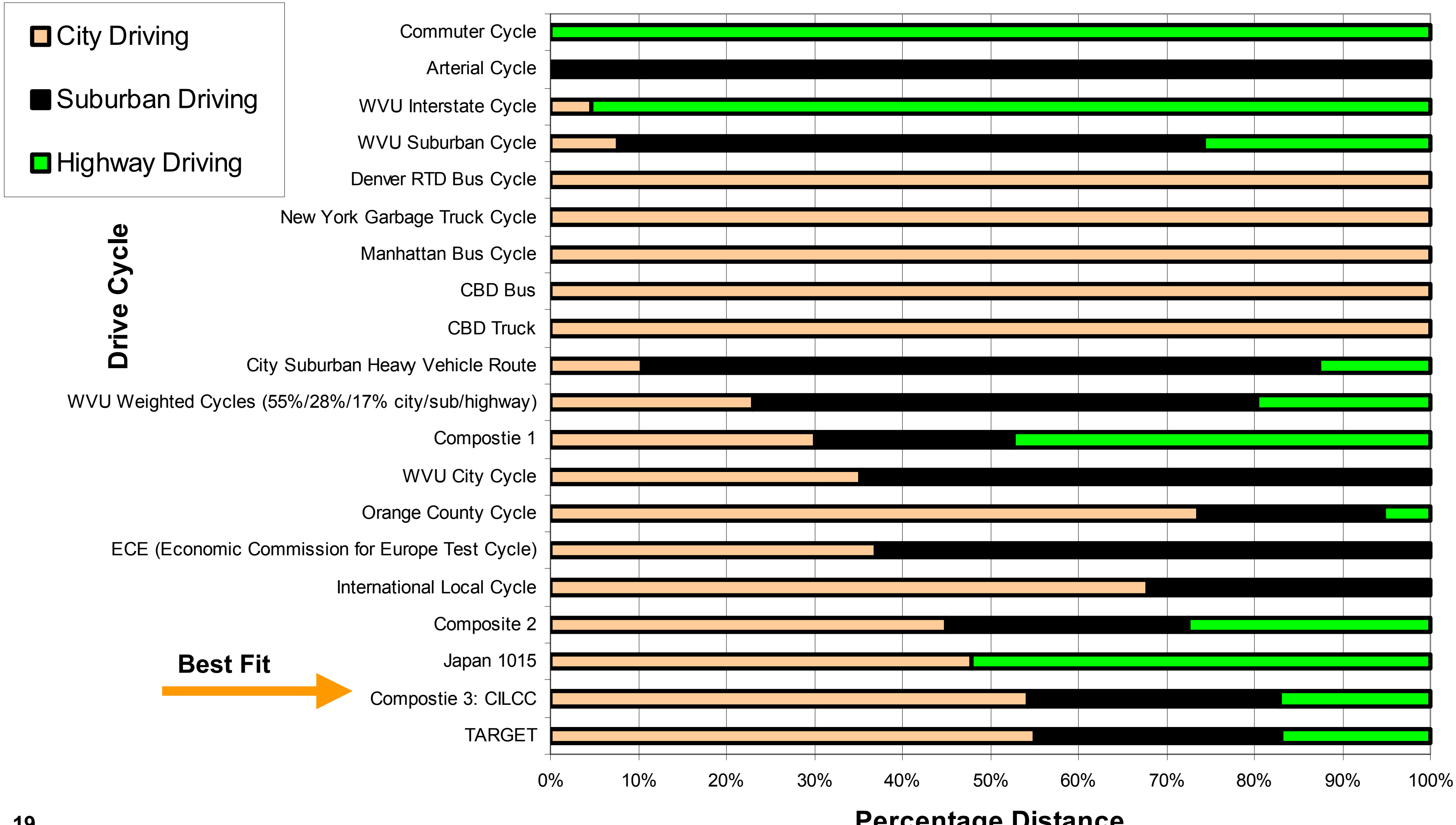
the CILCC was arranged to meet this distribution.



4th CRITERION

Speed Distribution Spread

representative driving



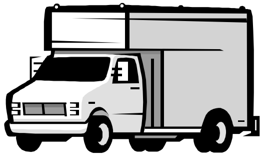
5th/6th CRITERION

Other Considerations for Testing

Weighted Cycles versus Composite Cycles

ease of SOC correct/ ease of execution

An appropriate element cycle not found:



- Remaining choices:
  - weighted cycles and
  - composite cycles

- Weighted cycles require more testing resources

- A composite cycle such as the CILCC is preferred

Why is Energy Storage SOC Important?

Conventional Vehicle testing:

- energy from combustion engine equals total energy to complete the cycle
- this energy is consistent from test run to test run
- no significant energy storage on board other than fuel

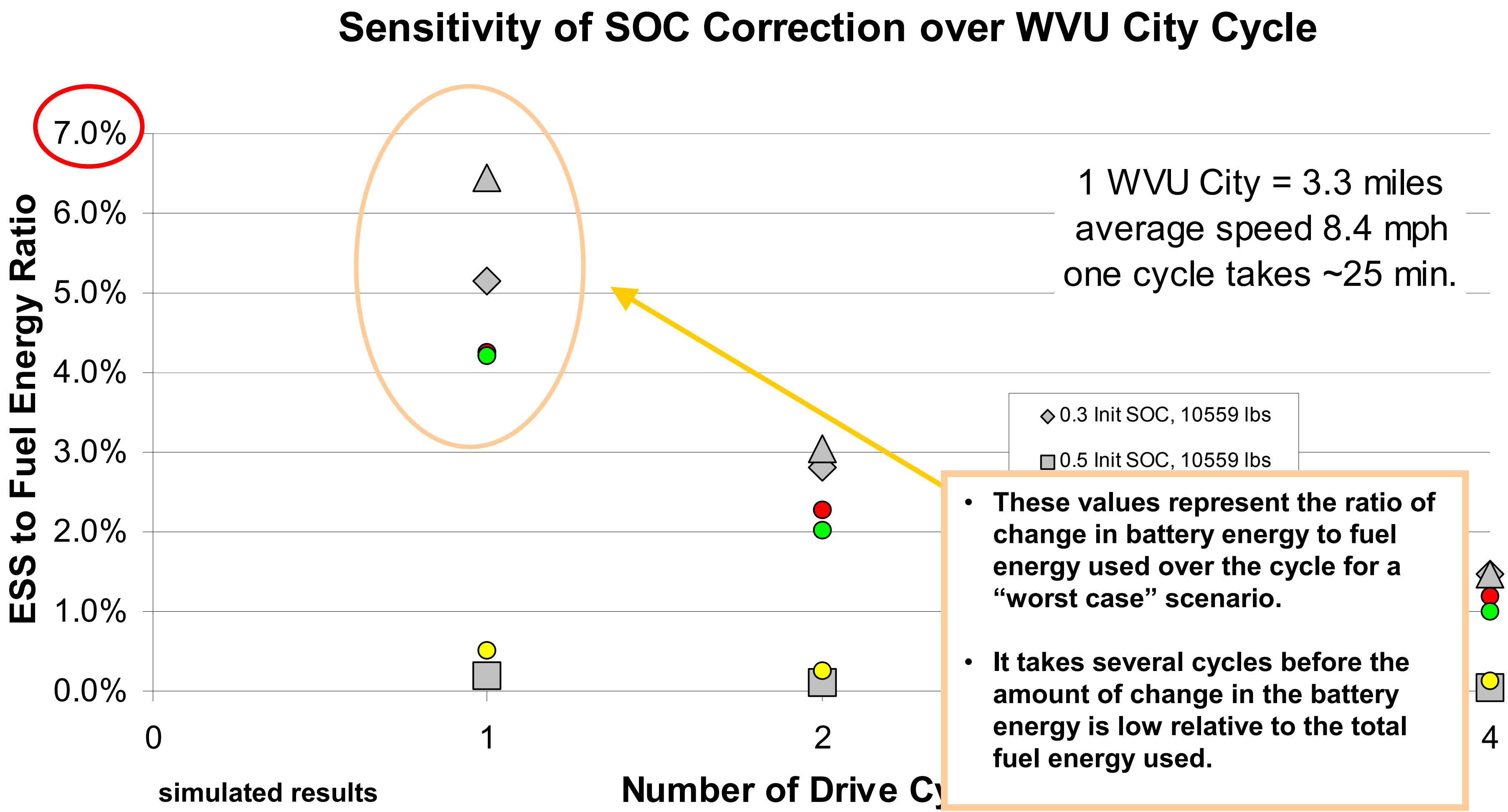
HEV testing:

- significant amount of energy stored in vehicle Energy Storage System (ESS)
- energy may be “taken from” or “added to” ESS during the cycle

Therefore, to compare fuel economy and emissions of HEV with a conventional vehicle, the net change in ESS energy must be less than 5% (ideally less than 1%) of the fuel energy used over the cycle*

*Reference: SAE J2711 *Recommended Practice For Measuring Fuel Economy And Emissions Of Hybrid-Electric And Conventional Heavy-Duty Vehicles*

Weighted and Element Cycles
Tend to be Sensitive to SOC Correction

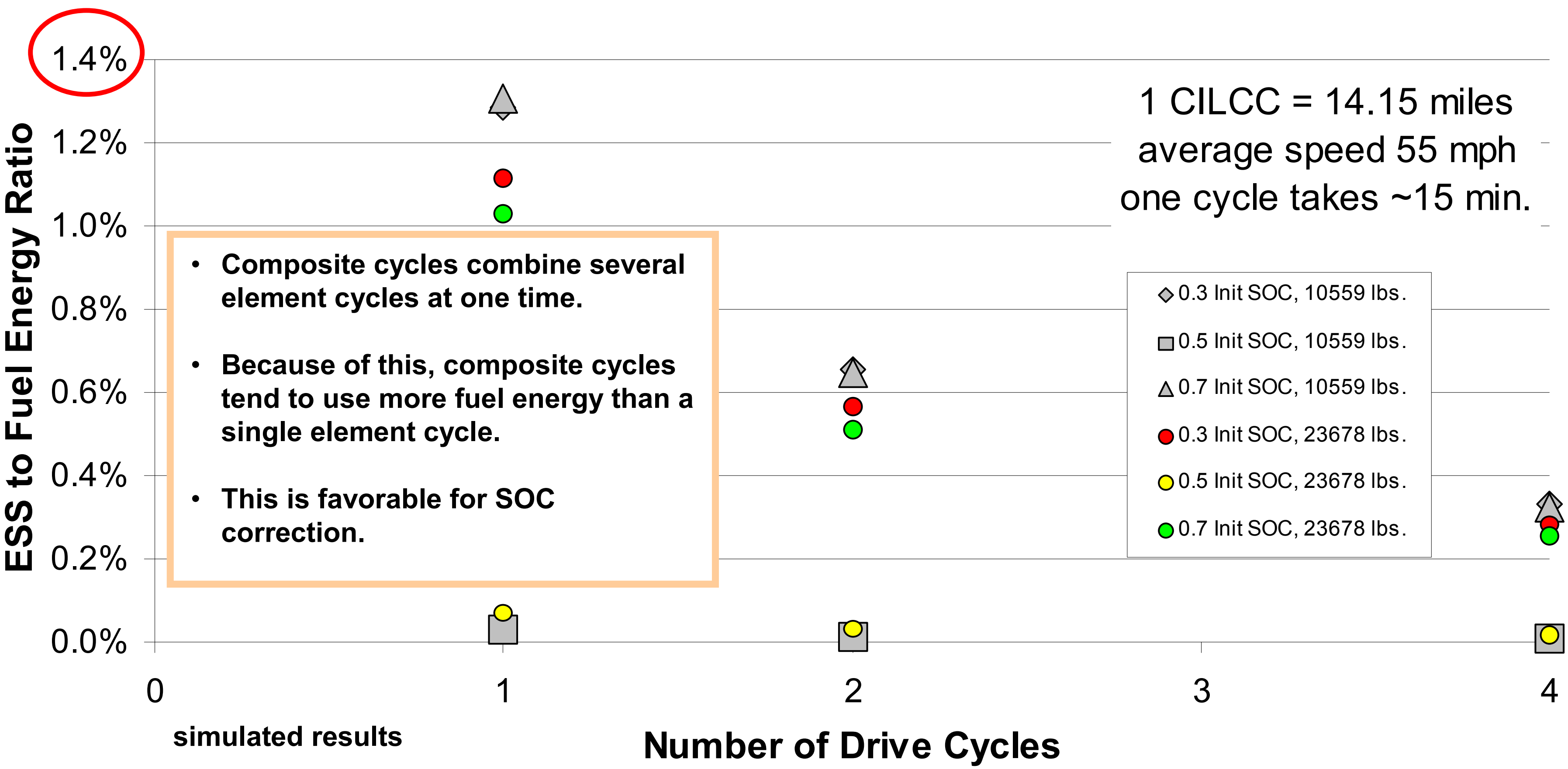


- These values represent the ratio of change in battery energy to fuel energy used over the cycle for a "worst case" scenario.
- It takes several cycles before the amount of change in the battery energy is low relative to the total fuel energy used.

To be within 2% energy, need 3-4 cycles (~2 hr), within 1%, need 4-5 cycles (up to 2.5 hr)

Composite Cycles
Tend to be Less Sensitive to SOC

Sensitivity of SOC Correction over CILCC Cycle



within 2% at first cycle, within 1% on 2 cycles

6th

CRITERION

Composite Cycle Uses Less Resources (dynamometer time)

ease of execution

WVU Weighted Cycles

- No SOC Correct
  - 1 CSHVR (0.5 hr)
  - 1 WVU City (0.4 hr)
  - 1 WVU Interstate (0.5 hr)
  - **TOTAL: 1.4 hrs**
- for SOC within 1% ess/fuel ratio:
  - 3 CSHVR (1.5 hr)
  - 5 WVU City (2 hr)
  - 2 WVU Interstate (1 hr)
  - **TOTAL: 4.5 hrs**

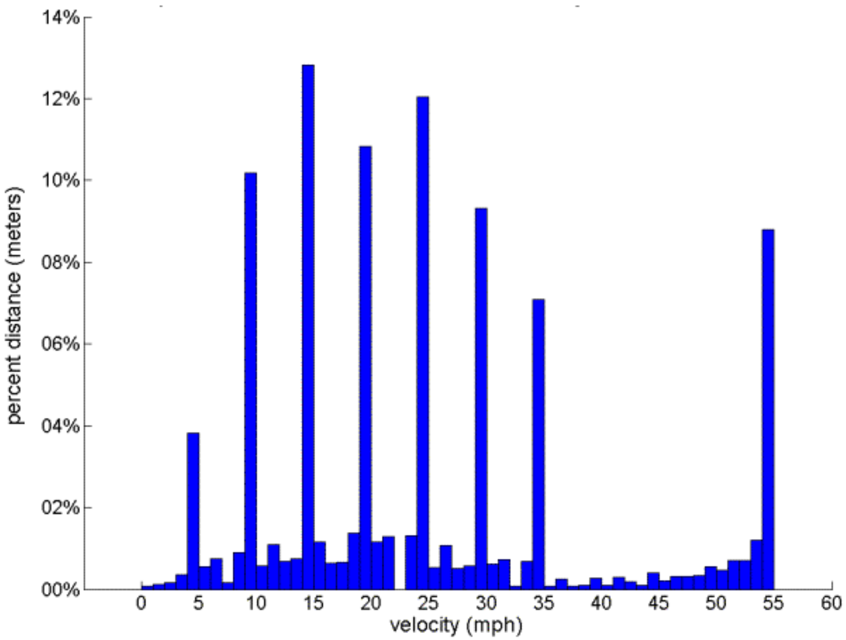
CILCC Composite Cycles

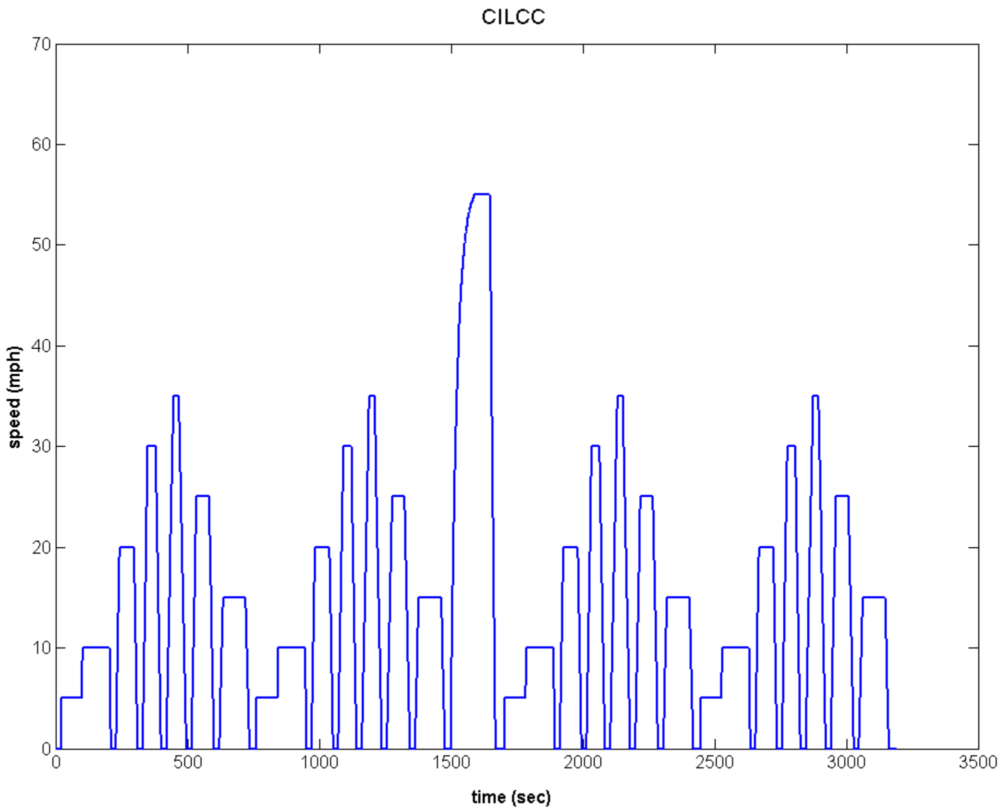
- No SOC Correct
  - 1 cycle (0.25 hr)
  - **TOTAL: 0.25 hrs**
- for SOC within 1% ess/fuel ratio:
  - 2 cycle (0.5 hr)
  - **TOTAL: 0.5 hr**

NOTE: Independent of emissions testing; multiple cycles may need to be run to measure emissions properly (2007 emissions targets) J2711 provides for SOC correction calculations if within 5%

the CILCC Cycle Chosen

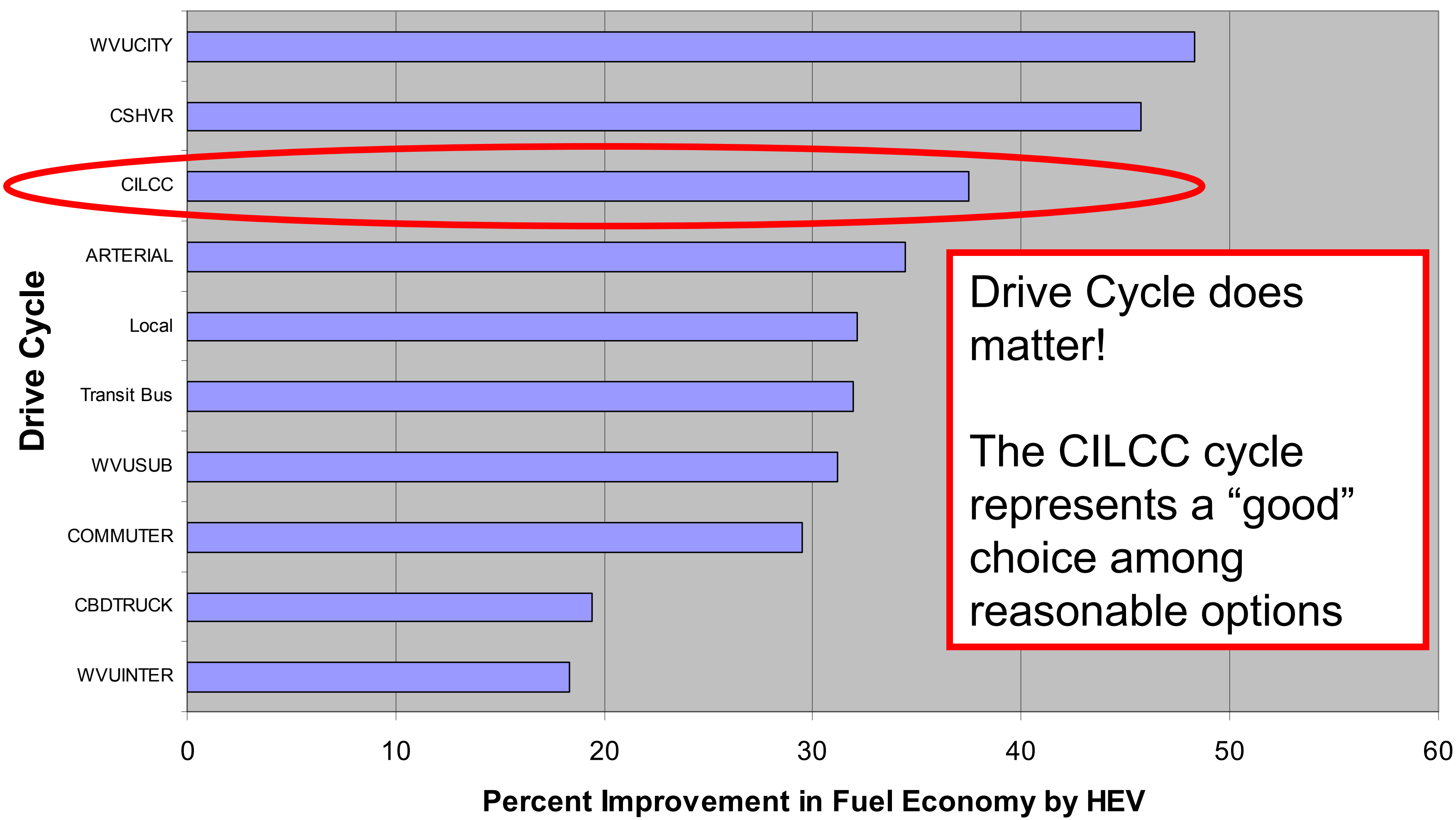
Composite International Truck Local Cycle and Commuter





Fuel Economy Improvement
Hybrid Advantage

based on vehicle simulation



Summary

- The CILCC[*] cycle chosen for Class 4-6 Urban Delivery Vehicle testing DOE AHHPS Program[**] (Eaton Team)

- The CILCC cycle meets basic criterion such as:
  - traction power requirements appropriate to the vehicle vocation
  - representative of actual customer driving patterns
  - ease of execution in both dynamometer and field testing

- Messages:
  - The CILCC cycle represents a “good” choice among reasonable options
  - CILCC is best fit to the data we have from the target customer
  - The drive cycle DOES matter!

[*] CILCC = Combined International Local Cycle and Commuter
[**] AHHPS = Advanced Heavy Hybrid Propulsion Systems Program

Acknowledgements

- Our Sponsors, the US Department of Energy, especially
  - Susan Rogers, US DOE *Office of FreedomCAR and Vehicle Technologies*
  - Graham Hagey, *Consultant*

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  - Robert Rehn, *NREL*
  - *the editorial reviewers at NREL*

- *The paper corresponding to this presentation available at 2004 SAE World Congress*