The National Academies of SCIENCES · ENGINEERING · MEDICINE

TRANSPORTATION RESEARCH BOARD

Modeling the Relationship Between Vehicle Speed and Fuel Consumption

Wednesday, March 14, 2018
2:00-3:30 PM ET

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Providers Program. Credit earned on completion of this program will be reported to RCEP. A certificate of completion will be issued to participants that have registered and attended the entire session. As such, it does not include content that may be deemed or construed to be an approval or endorsement by RCEP.

RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

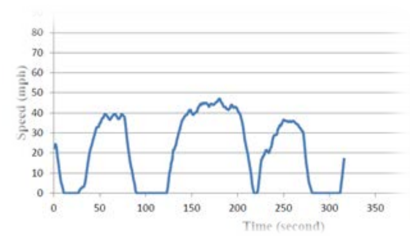
Purpose

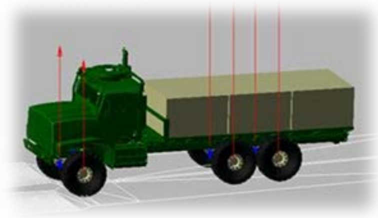
Discuss the relationship between vehicle speed and fuel economy as investigated by the U.S. Federal Highway Administration.

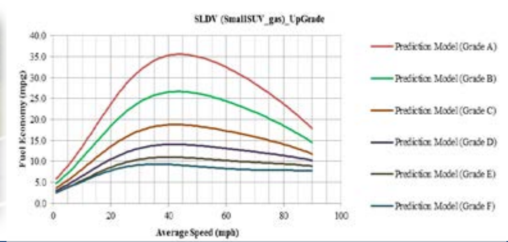
Learning Objectives

At the end of this webinar, you will be able to:

- Apply developed prediction models to estimate vehicle fuel consumption as a function of road grade level
- Assess the influence of traffic congestion level on fuel consumption
- Assess the influence of the number of signalized intersections on fuel consumption
- Assess the excess in fuel consumption due to road curvatures





Modeling the Relationship Between Vehicle Speed & Fuel Consumption

TRB Webinar

March 14, 2018

Acknowledgment

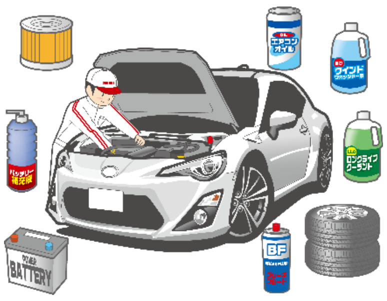
- U.S. DOT, FHWA DTFH61-14-C-00044: Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs.
- American Transportation Research Institute (ATRI) for its support.

Abbreviations

- AS: Average Speed in mph
- GR: Road Grade in percent (UGR upgrade, DGR: Downgrade)
- GR_{level}: Road Grade level (level A through F)
- SL: Speed Limit in mph
- NTCD: Number of Traffic Control Devices per mile (Average) (positive real number)
- FAC: Full Access Control facilities
- PNAC: Partial or No Access Control facilities
- LOS: Level Of Service
- DCA: Degree of curvature in degrees
- IRI: international Roughness Index
- PSD: Power Spectral Density
- PCAF: Pavement Condition Adjustment Factor

Overall Project Objective

- "…to improve the state-of-the-art in vehicle operating costs (VOC) estimation for use in benefit cost analysis."
  - Vehicle Fuel Economy (FE)
  - Non-Fuel Vehicle Operating Costs (VOC):
    - *Tire Wear*
    - *Oil Consumption*
    - *Repair and Maintenance*
    - *Mileage-Related Vehicle Depreciation*
  - Considerations to changes in vehicle technology, vehicle operating speeds, traffic management & driving cycles.



Project Team Organization

- **Federal Highway Administration**
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  - **Principal Investigators (university of Nevada, Reno)**
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    - Nevada Automotive Test Center
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    - Dynatest Consulting
      - **Non-Destructive Pavement Testing & Characteristics**
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        Per Ullidtz
        Gabriel Bazi

Section A, Elie Y. Hajj

OVERALL SCOPE

PHASE I

Full Access Control (FAC); all access via grade-separated interchanges

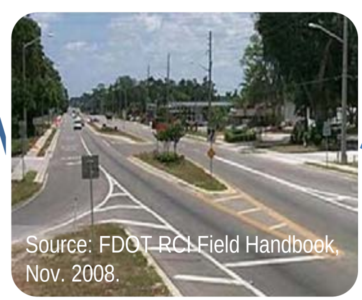
Partial Control; access via grade-separated interchanges & direct access roadways

No Access Control

PHASE I: MODELING THE RELATIONSHIP BETWEEN VEHICLE SPEED AND FUEL

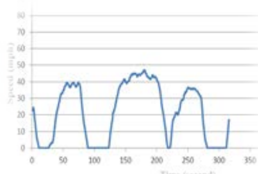

Source: TxDOT, Transportation Planning & Programming Division


Source: TxDOT, Transportation


Source: FDOT RCI Field Handbook, Nov. 2008.

Driving Cycle Development for Roadways with Full Access Control (FAC)

Fuel Consumption (FC) Estimates for FAC



Driving Cycle Development for Roadways with Partial or No Access Control (PNAC)

Fuel Consumption (FC) Estimates for PNAC

$$FE = f(AS, GR, SL, NTCD)$$

PHASE II

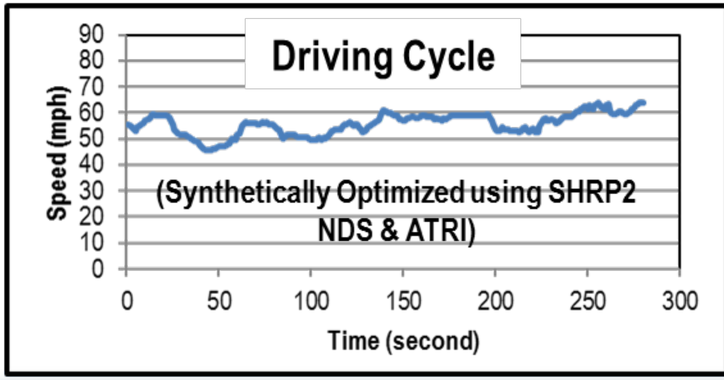
MODELING THE RELATIONSHIP BETWEEN PAVEMENT ROUGHNESS, SPEED, ROADWAY CHARACTERISTICS AND VEHICLE OPERATING COSTS

Effects of Road Curvature on Fuel Consumption

Incremental Fuel Consumption Due to Pavement Roughness

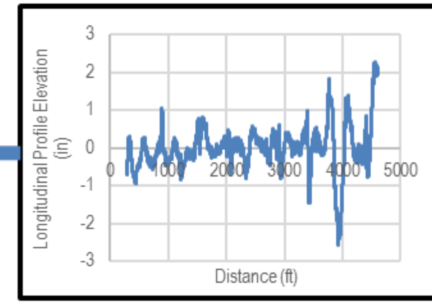
Effects of Infrastructure Physical & Operating Characteristics on Non-Fuel Vehicle Operating Costs (VOC)

Fuel Economy (FE) Simulation Process
Overall Approach

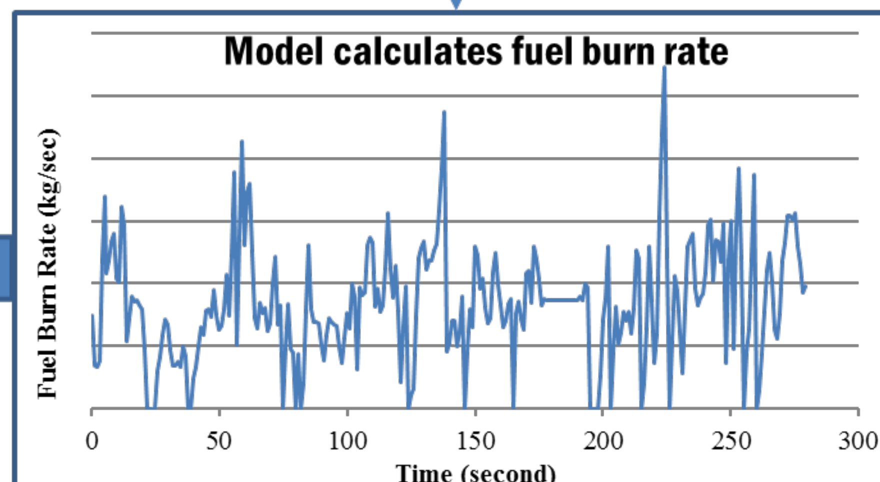


Physics-Based Vehicle Model

Road Grade
Road Profile
Rolling Resistance



Analogous process followed for Hybrid Electric (HE) vehicles

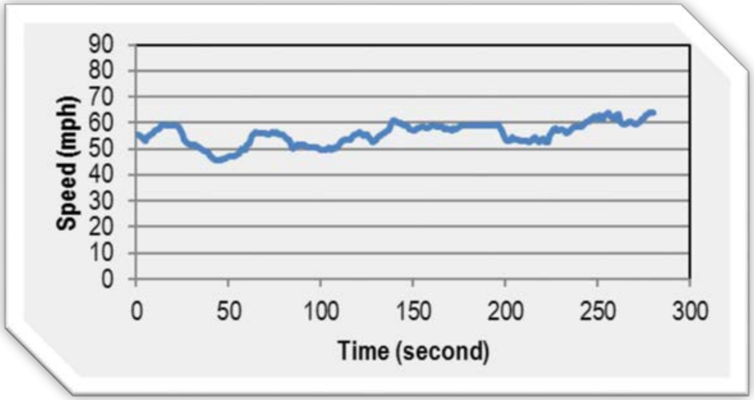


Fuel economy calculation

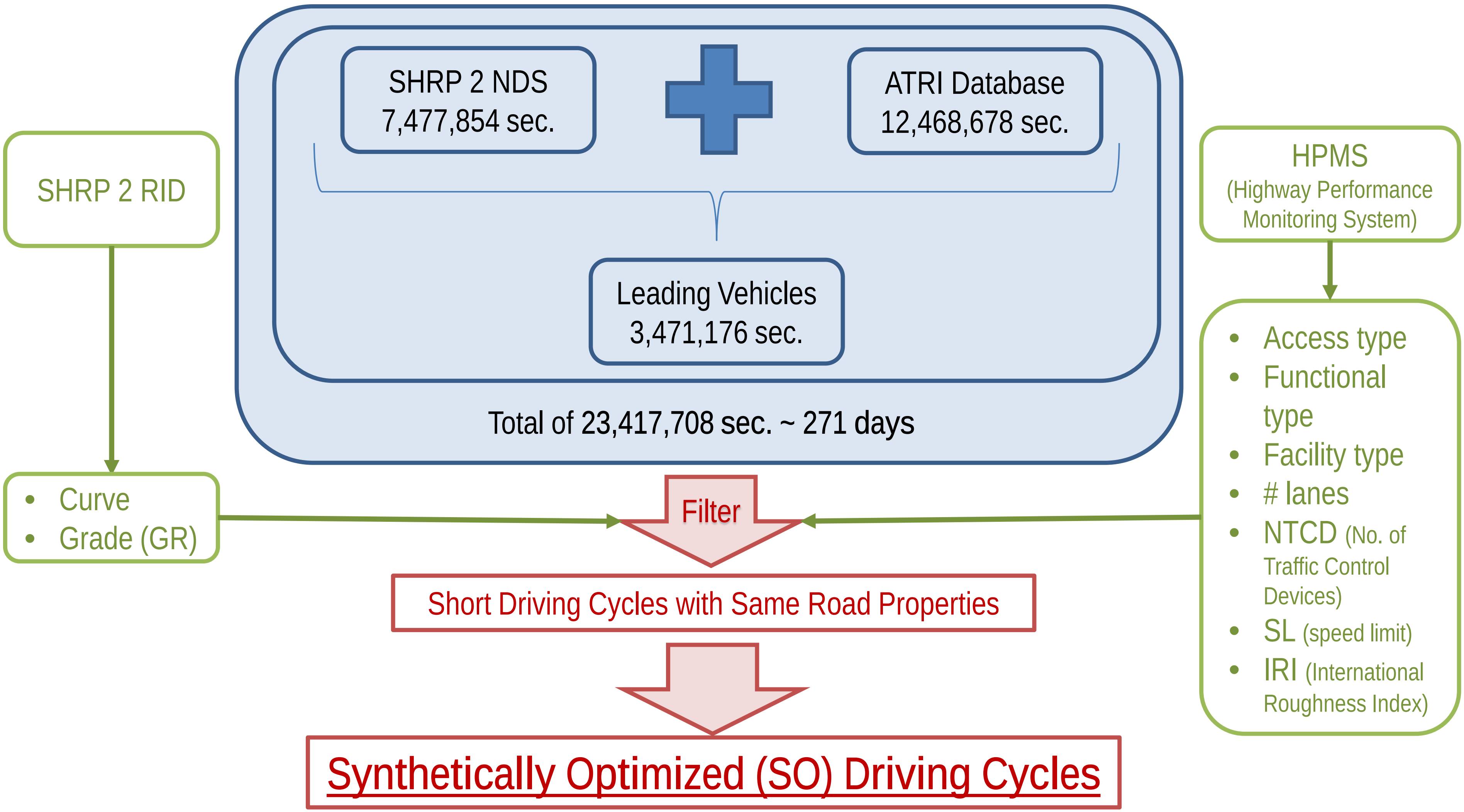
$$FE = \frac{\int_{Tstart}^{Tend}(speed)}{\int_{Tstart}^{Tend}(fuel\ burn\ rate)}$$

Section B, Hao Xu

DRIVING CYCLES



Development of Driving Cycles



Road Scenarios

- 45 full access control (FAC) scenarios.
  - 15 rural scenarios and 30 urban scenarios;
  - Horizontal curve level A;
  - Grade levels of A through C.
- 335 partial or no access control (PNAC) scenarios.
  - 186 rural scenarios and 149 urban scenarios;
  - Horizontal curve levels of A and B;
  - Grade levels of A through D.
- In all cases travel length longer than 5 miles was targeted.

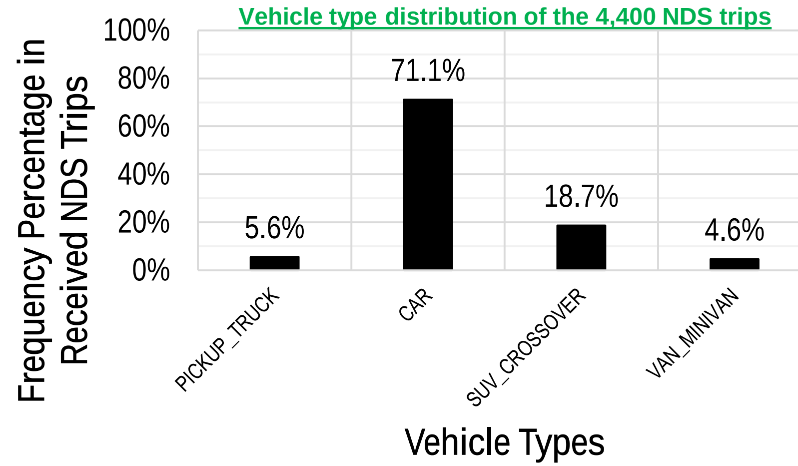
Traffic Condition and Up/Down Grade

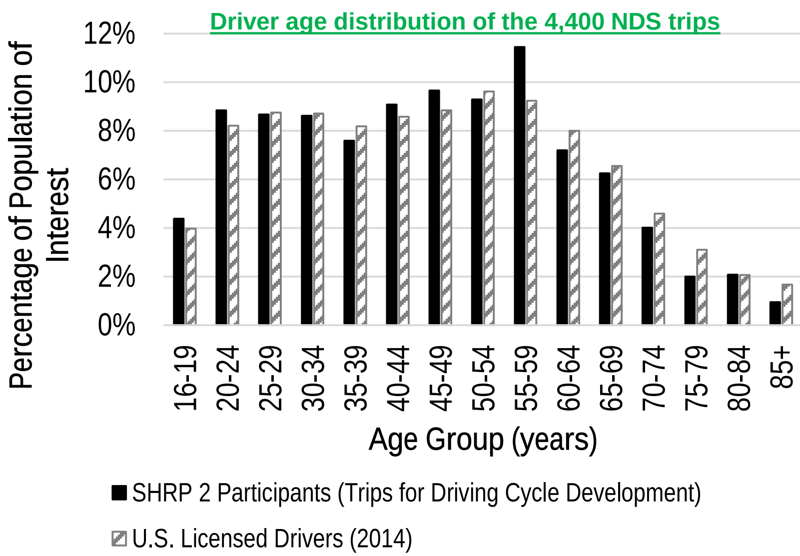
- Traffic condition: level of service (LOS)
  - Average travel speed of each trip snippet was calculated
    - Total travel distance divided by total travel time
  - Convert average travel speeds to traffic LOS

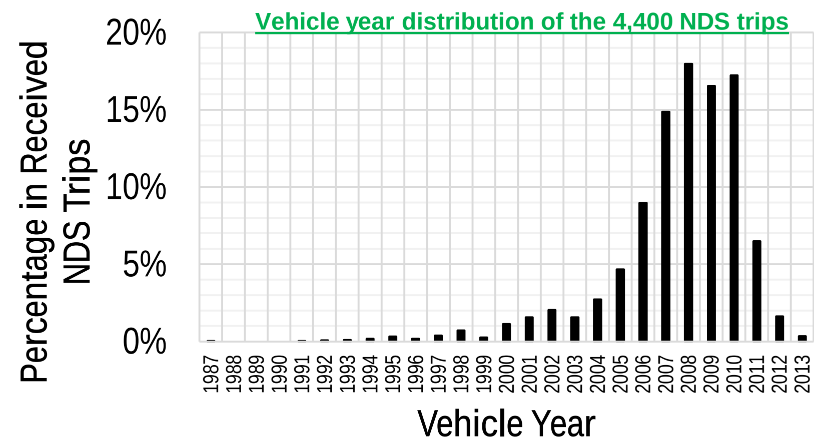
- Upgrade & downgrade condition
  - Same HPMS grade includes up & down situations
  - Elevation change of each trip snippet was used to determine the upgrade or downgrade
  - Driving cycles for upgrade & downgrade situations were considered separately.

Data: SHRP 2 Naturalistic Driving Study (NDS)
Driver Age & Vehicle Distributions

- 4,400-trip SHRP 2 NDS data
  - 6 NDS data collections sites of 6 states (urban/rural).
  - Each trip is ≥ 20-min
  - 7,477,854-sec data of NDS vehicles





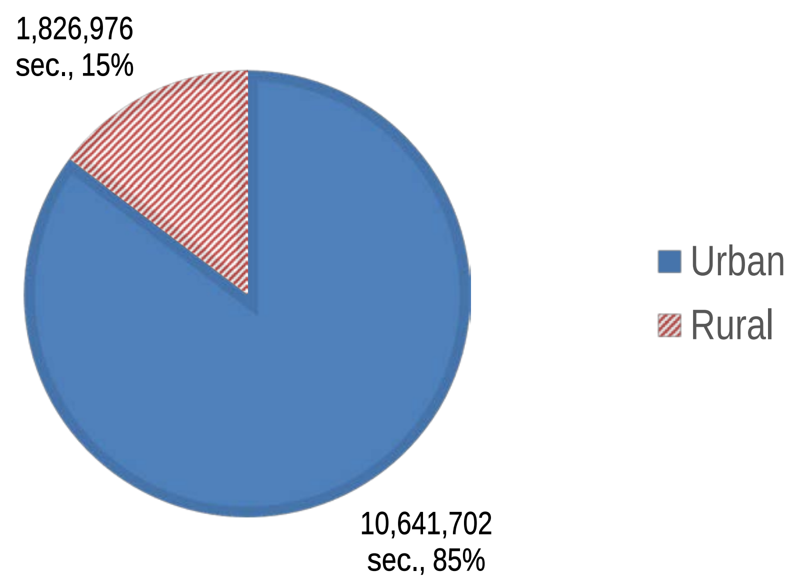


Note: the leading vehicle information not included in the charts.

Data

American Transportation Research Institute (ATRI) Truck Data

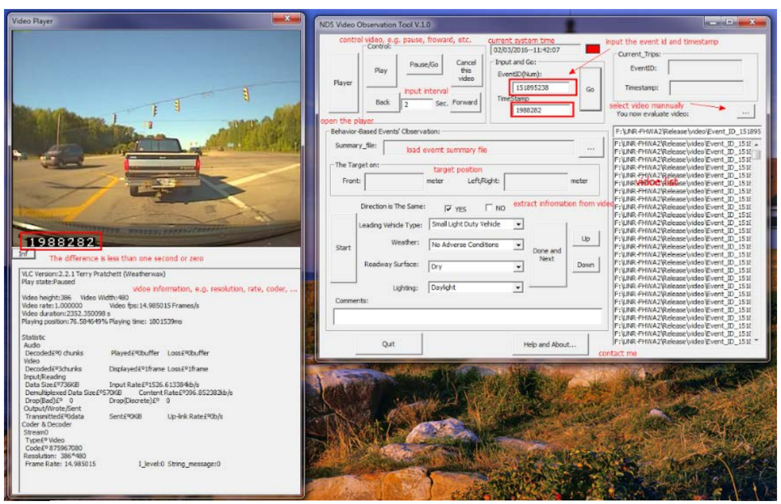
- Combination truck data were obtained from ATRI
  - ATRI offered a heavily subsidized agreement & support.
  - Truck trips collected in Seattle WA, Tampa FL & Buffalo NY (3 of the 6 NDS data collection sites).
  - 12,468,678-second truck data records.
  - Trip data were collected for 2 weeks in October 2015.



Data

Leading Vehicle Data Processing

- NDS (Naturalistic Driving Study) leading vehicle data extraction:
  - Using NDS front videos and radar data: the distance range & rate of range change between a NDS vehicle and the leading vehicle.
  - Method was used in *CARB/Sierra 2004 Sacramento Ramp Driving* & *Caltrans/CARB 2000 California Route Driving* studies.
  - A tool was developed to synchronize the front video and NDS data.
  - Total of 3,246,160-second radar data from 46,281 trip snippets.

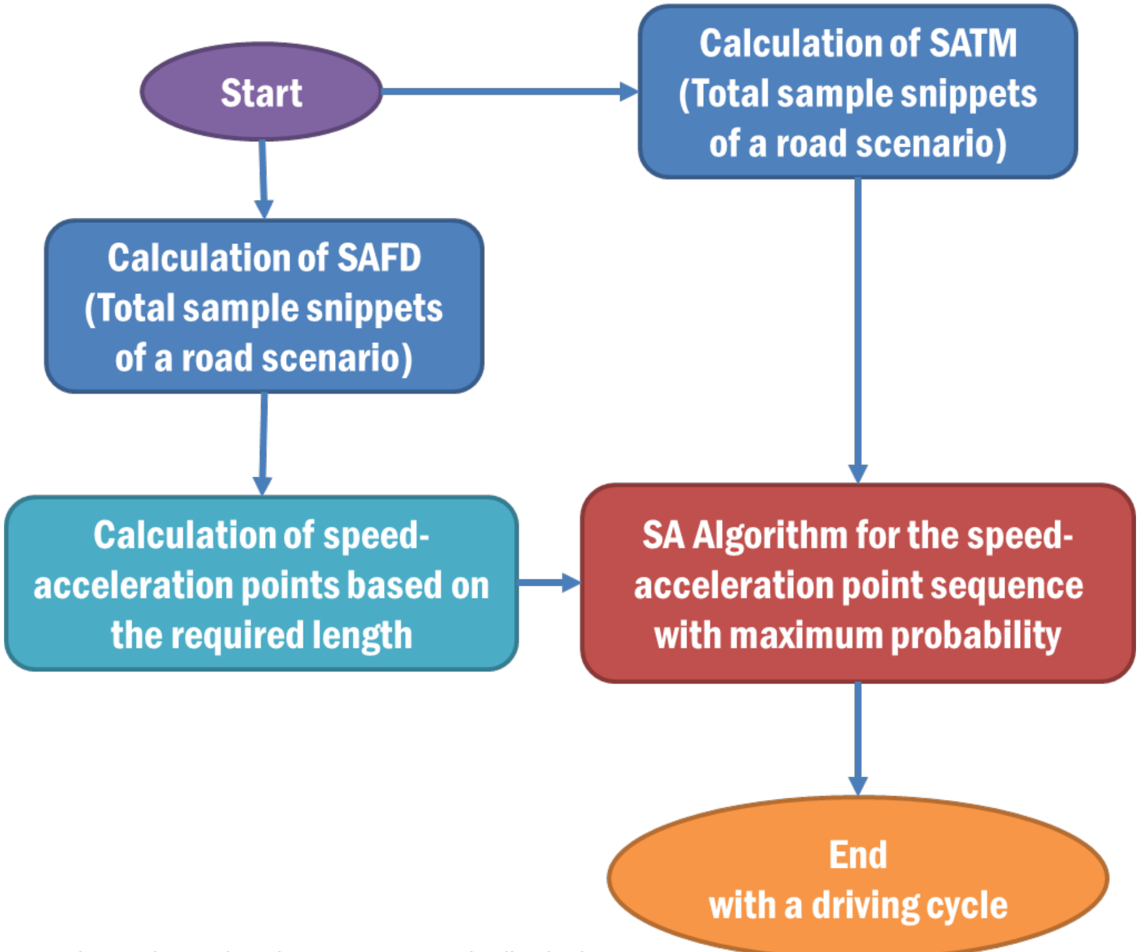


User interface of the NDS Front Video Review Tool.

Sample of a NDS front video frame.

Driving Cycle Development

Synthetic Optimization (SO) – Flow Chart



- Better representing the driving pattern of total trip samples
- Second-by-second change of speed & acceleration is actually observed in trip samples.
- Minimize the impact of possible map-matching errors in trip snippets.

SAFD (Speed-Acceleration Frequency Distribution)

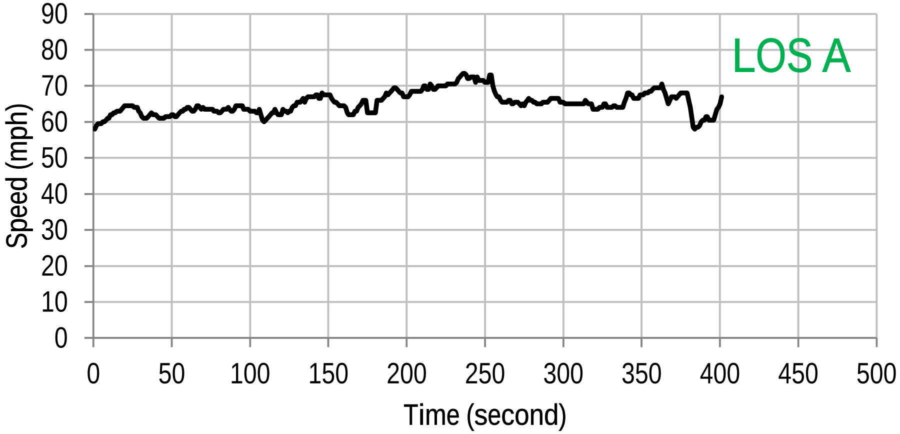
SATM (Speed-Acceleration Transition Matrix)

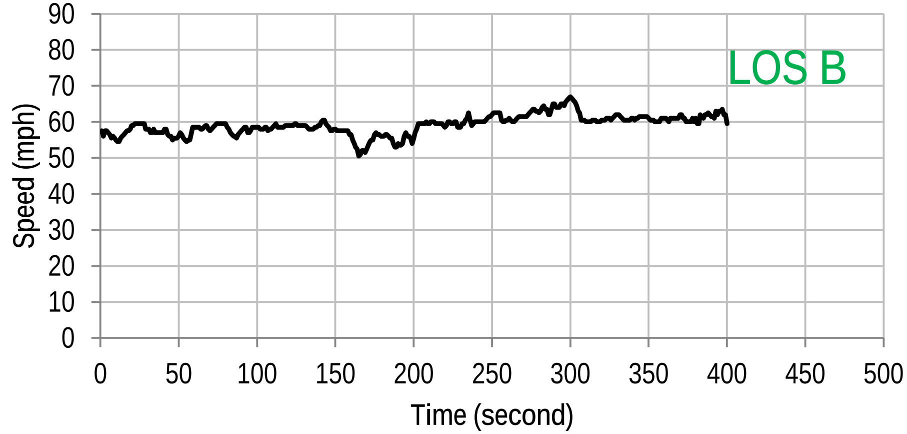
SA (Simulated Annealing)

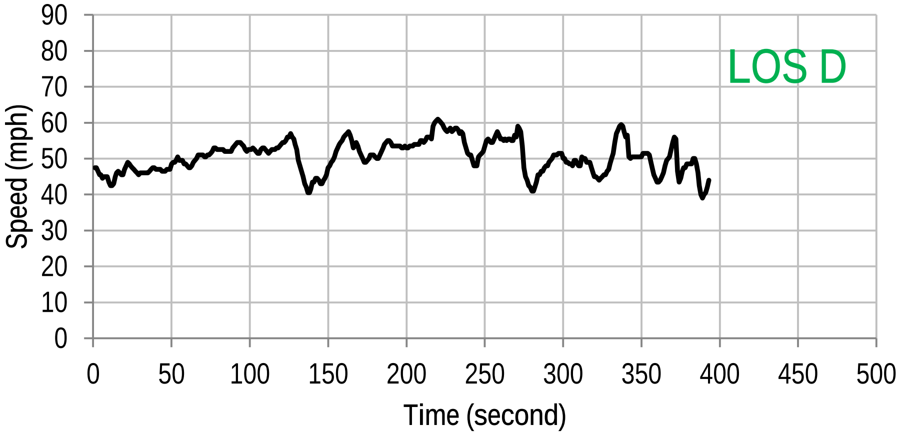
Results of the Driving Cycles Development

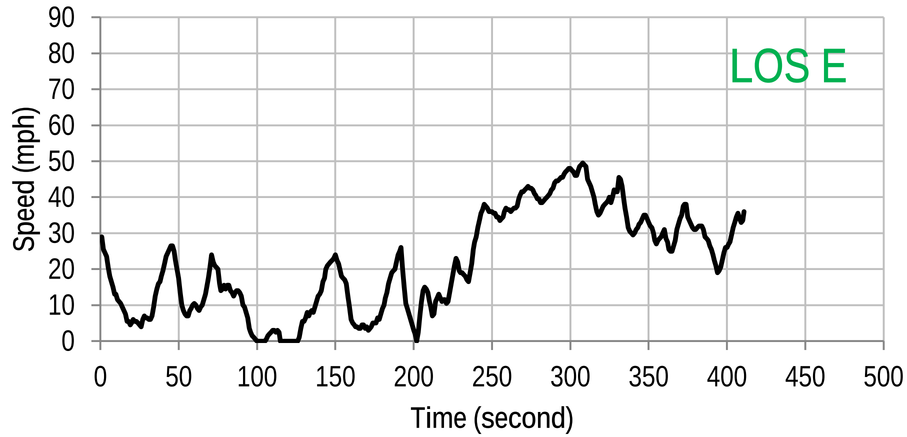
Examples: LOS A, B, D & E

Highway scenario with properties of urban area, full access control, interstate highway, 3 or more lanes in each direction, speed limit of 60 mph, horizontal curve classification A, & road grade C.





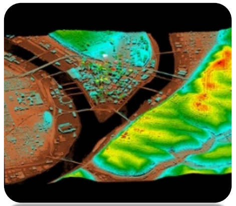




Results of the Driving Cycles Development

Overall Summary of Developed Driving Cycles

- Comprehensive dataset for driving cycles.
  - SHRP 2 RID
  - SHRP 2 NDS
  - USGS NED
  - ATRI truck data



Example of USGS NED data

- *654 unique synthetic optimization (SO) driving cycles.*
  - 212 driving cycles for Full Access Control (FAC) Highway.
  - 442 driving cycles for Partial or No Access Control (PNAC) Highway.

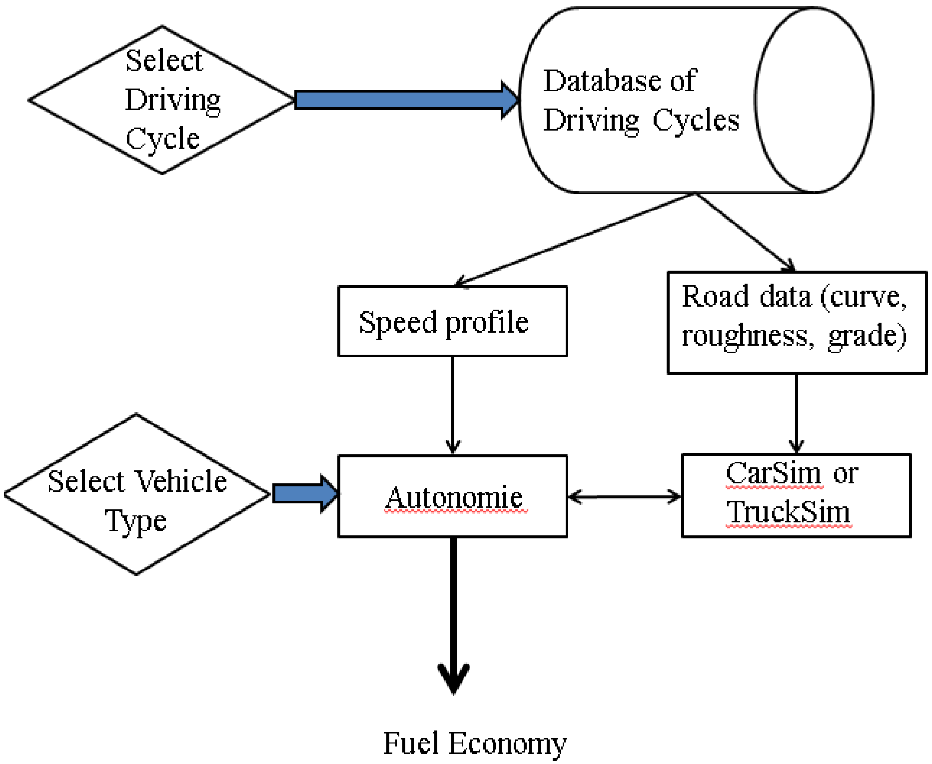
- Driving cycles are next used as input for fuel economy simulations.

Section C, Muluneh Sime

VEHCILE SIMULATION MODELS

Full Vehicle Models

- Physics-based models built to represent a range of vehicles
- Each simulation model consists of 4 subsystems:
  - – **Chassis**, including tires, suspension, aero & rolling resistance loads
  - – **Power train**, including engine, transmission, differentials, accessories, & control systems
  - – **Roads**, including grades, curves, & roughness
  - – **Driving cycles**, i.e., speed as a function of time



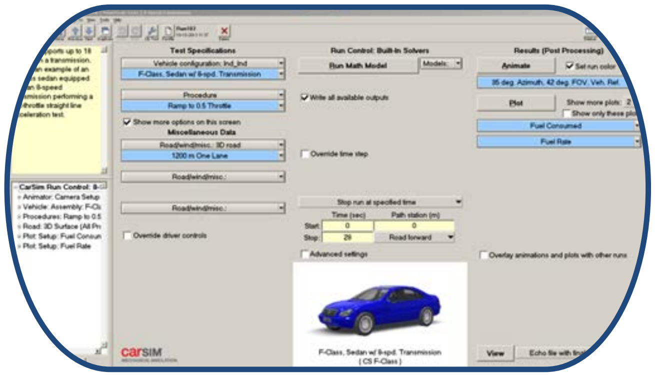
Physics-Based Vehicle Models

20 Vehicle Chassis

Small light duty vehicles (6 SLD vehicles)
Subcompact
Compact
Mid size sedan
Large sedan
Small SUV
Minivan

Combination trucks (2 vehicles)
Tractor trailer

Large light duty vehicles (5 LLD vehicles)
Small Pickup
Large SUV
Class 1 truck
Class 2 truck
Commuter van



Truck with 3 axles (1 vehicle)
Vocational Dump Truck
(Gravel truck)

Busses (3 vehicles)
School bus
City bus
Long distance bus

Two axle trucks with dual rear tires (3 vehicles)
Class 3 truck
Class 4 truck
Class 5 truck

Simulated Vehicle Fleet

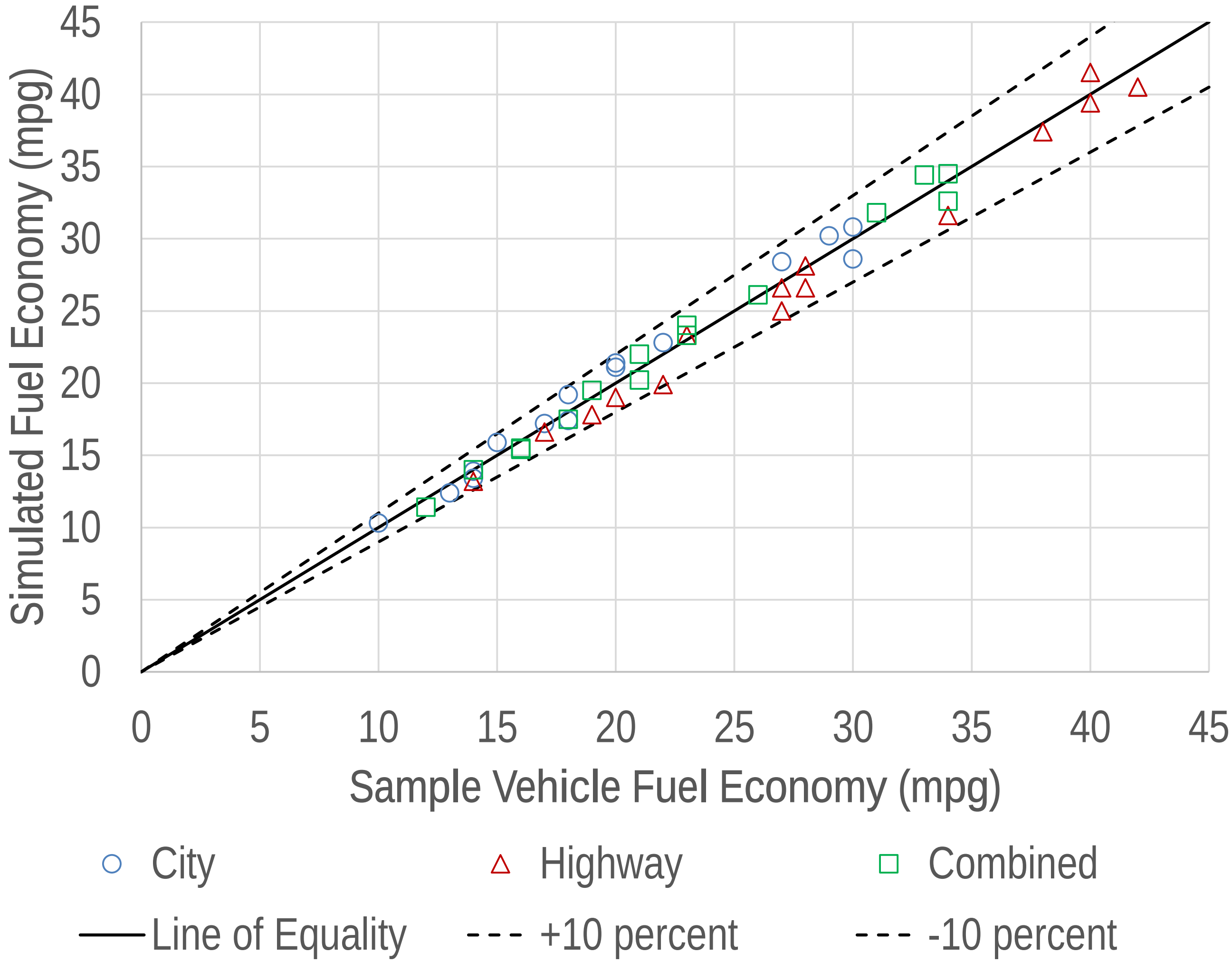
- 30 vehicles simulated (20 chassis with different engine types)
  - Gasoline
  - Diesel
  - Gasoline-Ethanol blend of up to 85% ethanol (E85)
  - Hybrid-Electric (HE)
  - Liquid Natural Gas (LNG).

Vehicle Simulation Model Verification

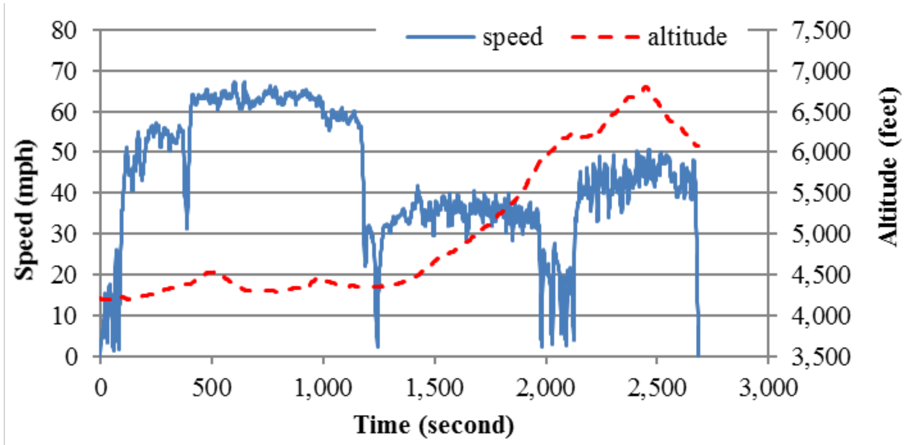
- **Verification Effort:** Simulate vehicle operation on known speed cycles and compare simulated fuel economy with measured data.

- Three sources of data used:
  - LDV (light duty vehicles) data for EPA drive cycles is published data. Sample vehicle models were run for city, highway, & combined drive cycle fuel economy.
  - Two axle, 6 wheel truck data was obtained through physical testing.
  - Class 8 truck data obtained from Oak Ridge National Labs (ORNL).

Light Duty Vehicle (LDV) Model Verification Results



Vehicle Model Verification Example: Class 5 Truck

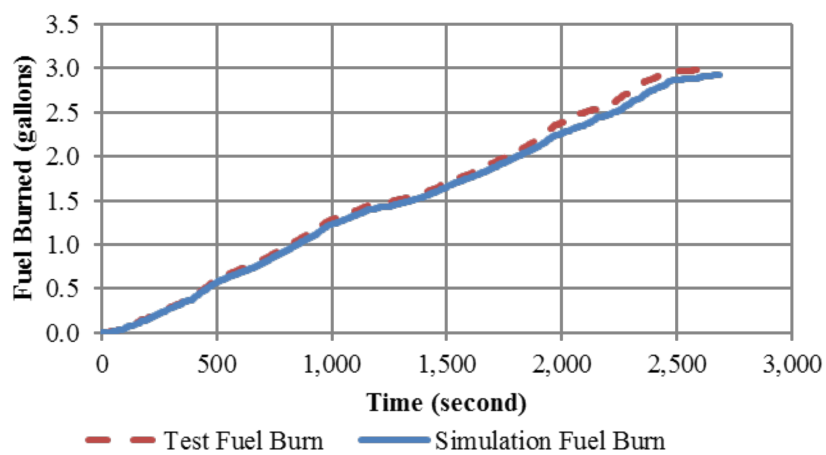


- Instrument a test vehicle & operate over a range of drive cycles & road grades
- Create simulation environment for virtual testing
- Compare model & test results

  32.8 mile route

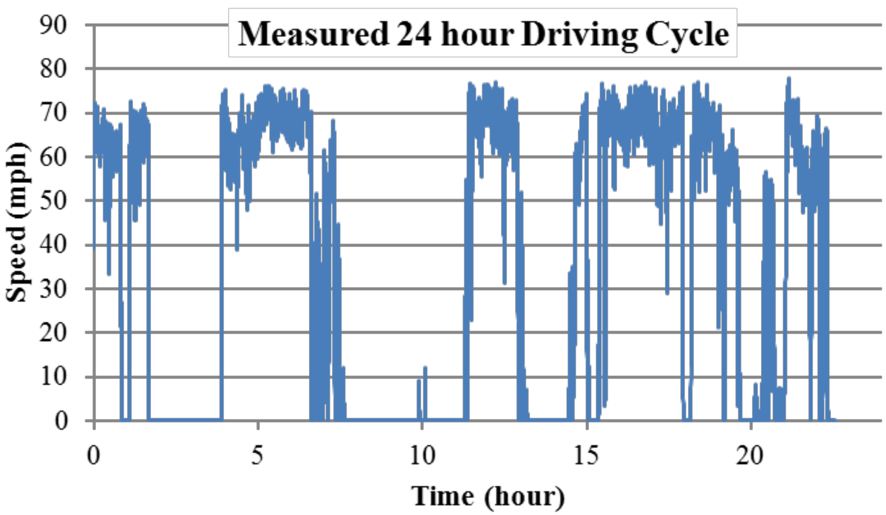
  Test Vehicle: 10.9 mpg | Simulation Vehicle: 11.1 mpg

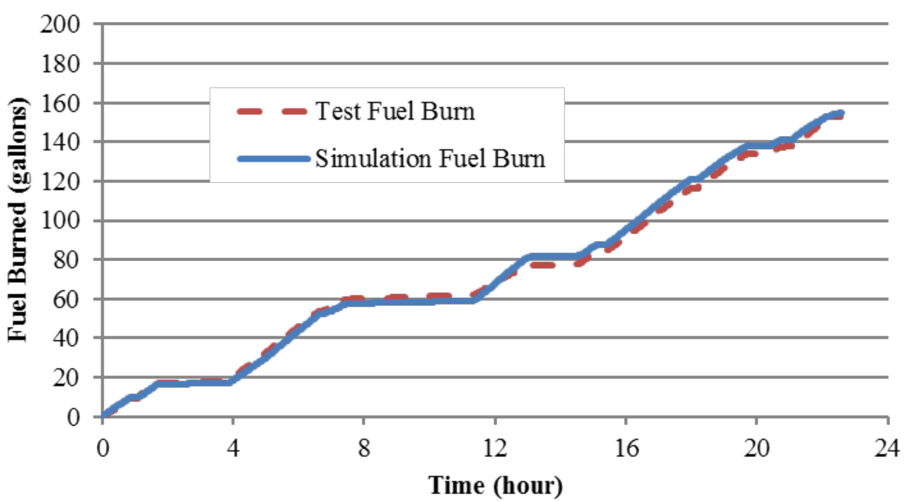
  Difference in mpg = 1.8 %



Vehicle Model Verification Example: Class 8 Truck

- Data obtained from Oak Ridge National Laboratories
  - Heavy Truck Duty Cycle (HTDC) project sponsored by the US Department of Energy's (DOE's) Office of Freedom Car and Vehicle Technologies.
  - Test cycle was 764 miles
  - Vehicle weight 53,000 lb
  - Test results: 5.0 mpg | Simulation result: 4.95 mpg





Road Conditions: Grades

- Phase I considered only smooth surface pavements with no curvatures (i.e., straight).
- Upslope (+) & downslope (-) grades are included (12 grades total).

Road Grade Classification (GR_{level})	Grade (%)	Grade Used in Simulations (%)
A	0.0 – 0.4	±0.20
B	0.5 – 2.4	±1.45
C	2.5 – 4.4	±3.45
D	4.5 – 6.4	±5.45
E	6.5 – 8.4	±7.45
F	8.5 or greater	±10.0

Road Conditions: Curvatures

- Phase II considered influence of road curvature on fuel economy (smooth pavement).

Curve Level	Radius of Curve, R (ft)		Radius Value Used in Vehicle Simulations (ft)	Degrees of curvature, DCA, Used in Vehicle Simulations (°)
	Min	Max		
A	1,637	Straight	Straight	0.0
B	1,061	1,637	1,349	4.25
C	682	1,061	871.5	6.58
D	412	682	547	10.48
E	205	412	308.5	18.58
F	0	205	102.5	55.90

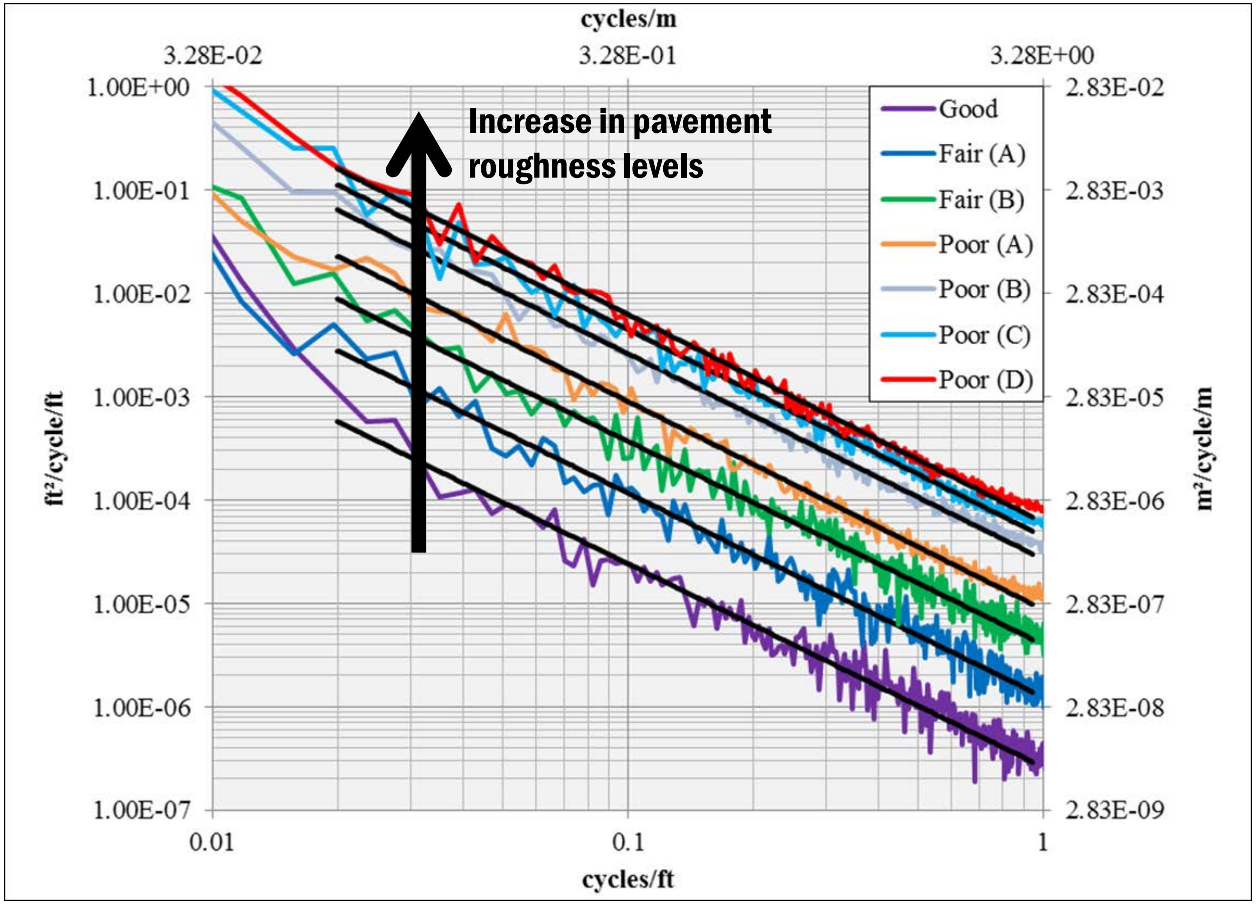
Road Conditions: Roughness Levels

- Phase II considered incremental fuel consumption due to pavement roughness.

Pavement Surface Condition Rating		Range of International Roughness Index, IRI	
		inch/mile	m/km
Good		≤ 95	≤ 1.50
Fair	Fair (A)	96-119	1.51-1.88
	Fair (B)	120-170	1.89-2.69
Poor	Poor (A)	171-200	2.70-3.16
	Poor (B)	201-220	3.17-3.48
	Poor (C)	221-320	3.49-5.05
	Poor (D)	> 320	> 5.05

Spatial Power Spectral Density (PSD) for Selected Roughness Levels

- PSD defines both amplitude & frequency characteristics of the rough pavement.
- Visualization of the relative differences in pavement roughness between classifications of pavement surface conditions.

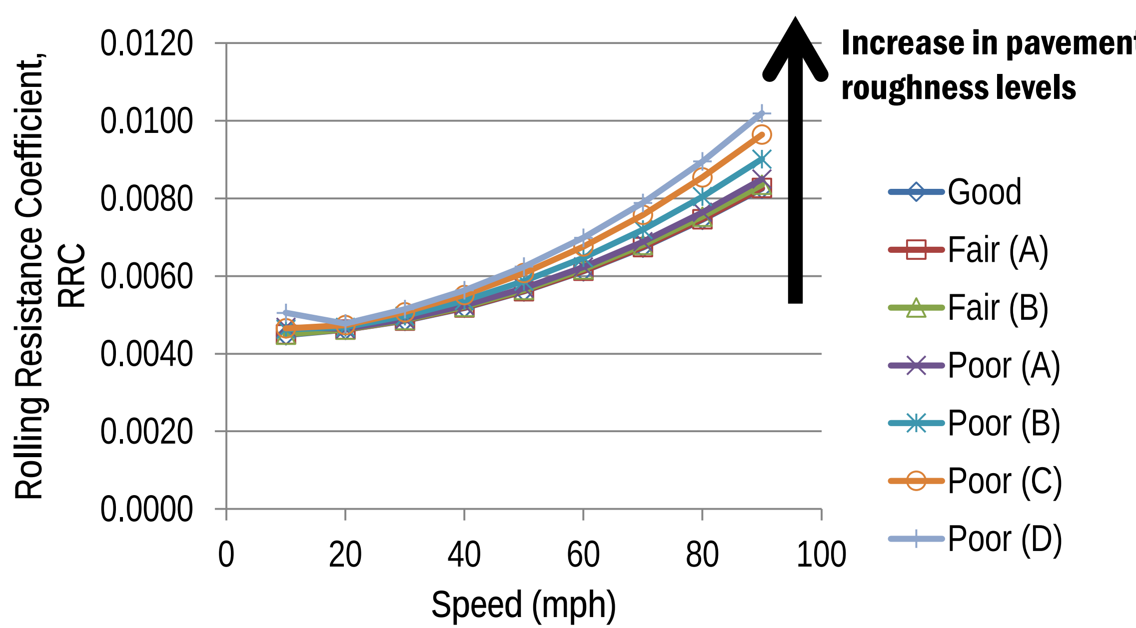


Rolling Resistance (RR) Components

- Rolling resistance is assumed to consist of 3 components
  - Rolling resistance of a tire on a smooth surface
  - Additional rolling resistance force of the tire due to pavement roughness
  - Additional rolling resistance due to suspension power dissipation

- *Rolling resistance force is a function of* ***pavement roughness amplitude &*** ***frequency*** *content*

Subcompact Car Example Results



Fuel Economy (FE) Simulations

- 30 vehicle models were run using speed cycles & defined road characteristics to calculate fuel economy.

- Smooth straight roads with +/- grades
  - 15,516 simulations

- Smooth roads with curvatures & +/- grades
  - 34,822 simulations

- Straight roads with a range of roughness levels & zero grade
  - 1,890 simulations

Over 52,000 simulations

Section D, Elie Y. Hajj

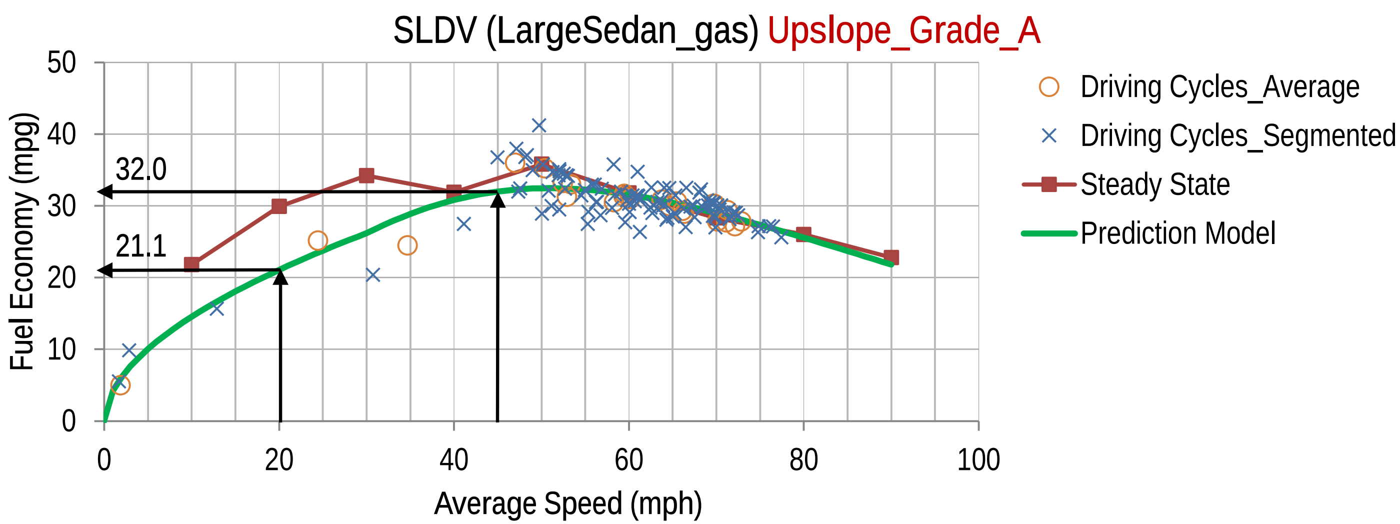
FUEL ECONOMY (FE) PREDICTION MODELS

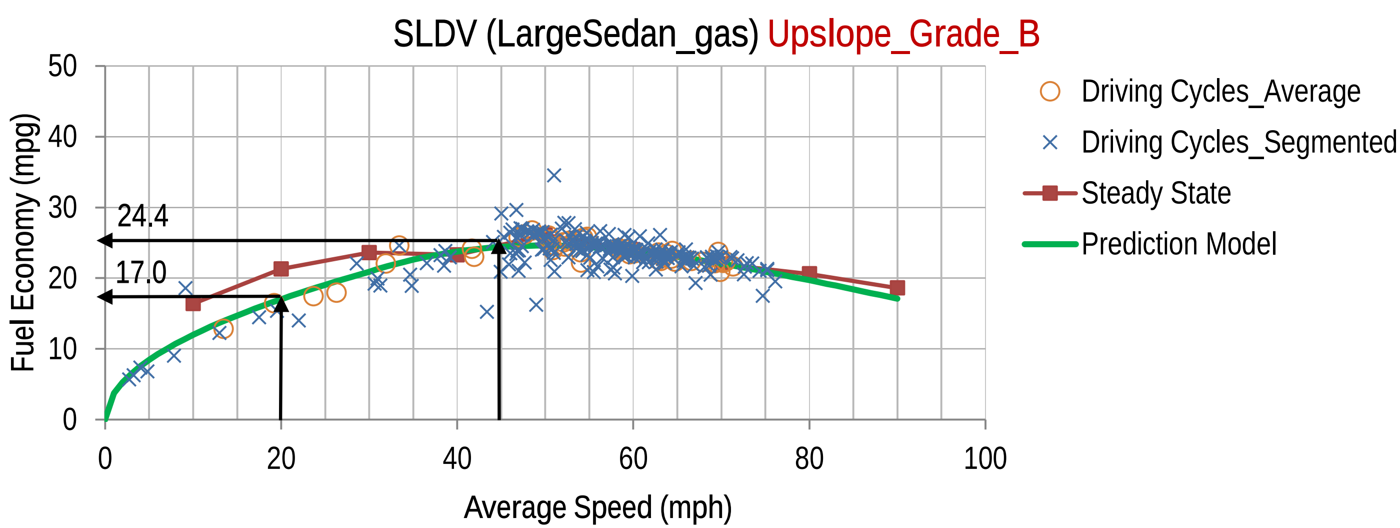
Development of Fuel Economy Prediction Models
(Regression Equations)

- Conducted multi-variable regression analyses of the FE simulation results
  - For each of the 30 vehicle models separately.
- Influential predictor variables were statistically determined.
  - Considered linear & logarithmic transformation of predictor & response variables.
  - Pairwise terms examined.
  - Predictor variables: *AS, UGR, DGR, AS/SL, NTCD*
- Regression models for upslope/downslope grades, FAC & PNAC facilities.
  - FE prediction models for smooth & straight roadways.
  - Reduction in fuel economy due to curvature (RFEC) prediction models.
  - Pavement damage adjustment factors for various roughness levels.

AS: Average Speed in mph
GR: Road Grade in % (UGR upgrade, DGR: Downgrade)
SL: Speed Limit in mph
NTCD: Number of Traffic Control Devices per mile
FAC: Full Access Control facilities
PNAC: Partial or No Access Control facilities

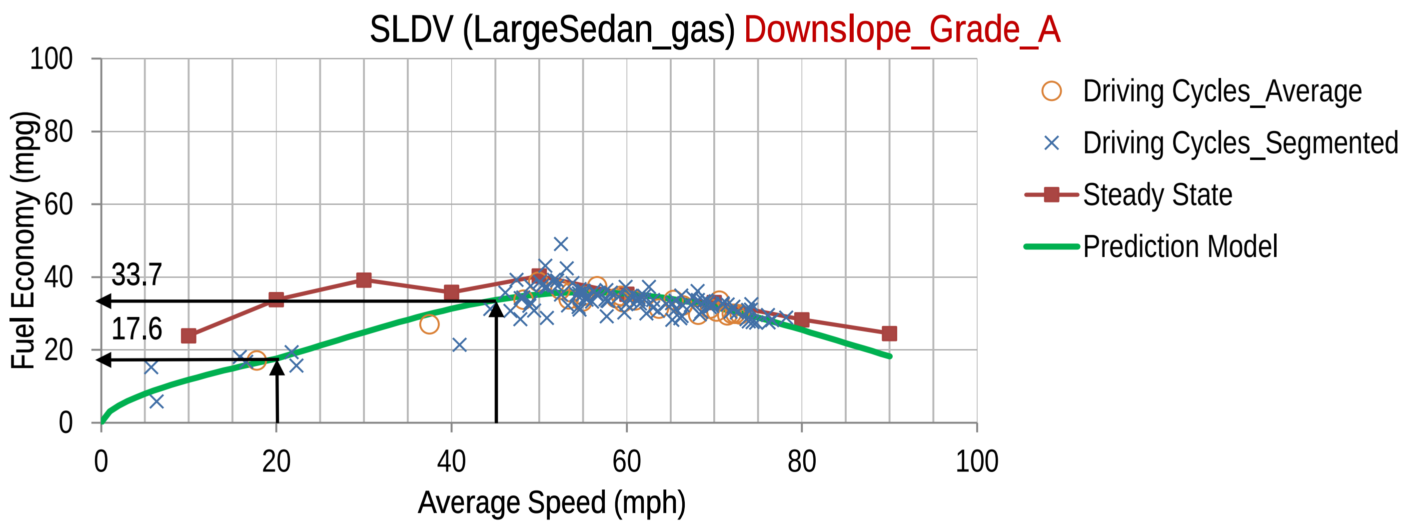
Fuel Economy Prediction Models
Full Access Control (FAC) – Upslope Grade, Large Sedan, Gasoline

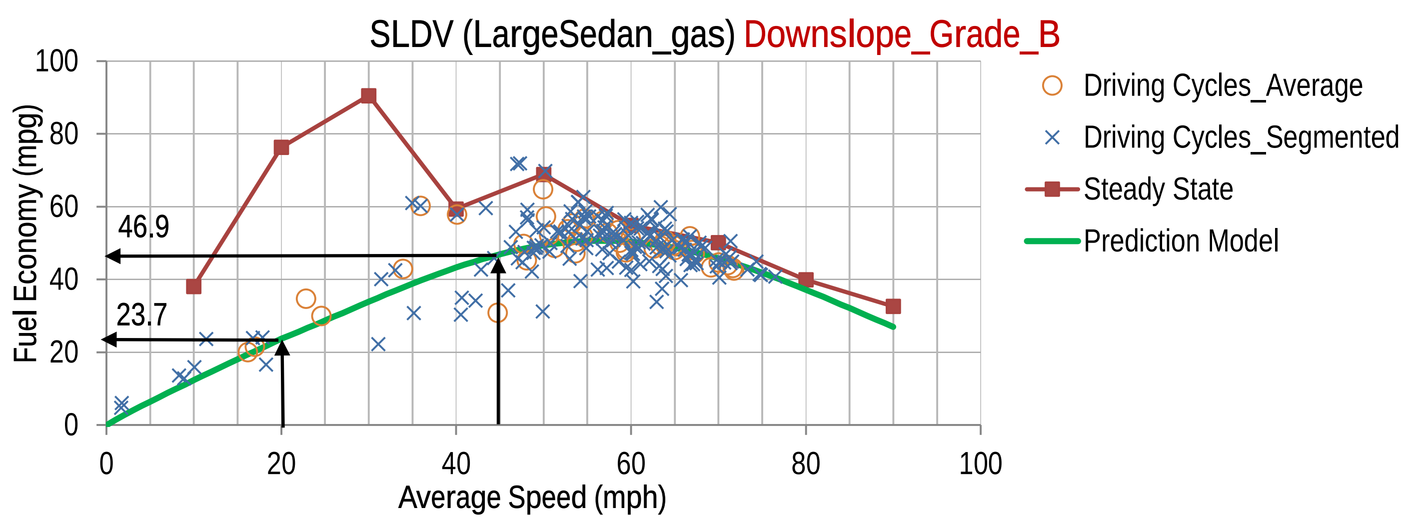




Fuel Economy Prediction Models

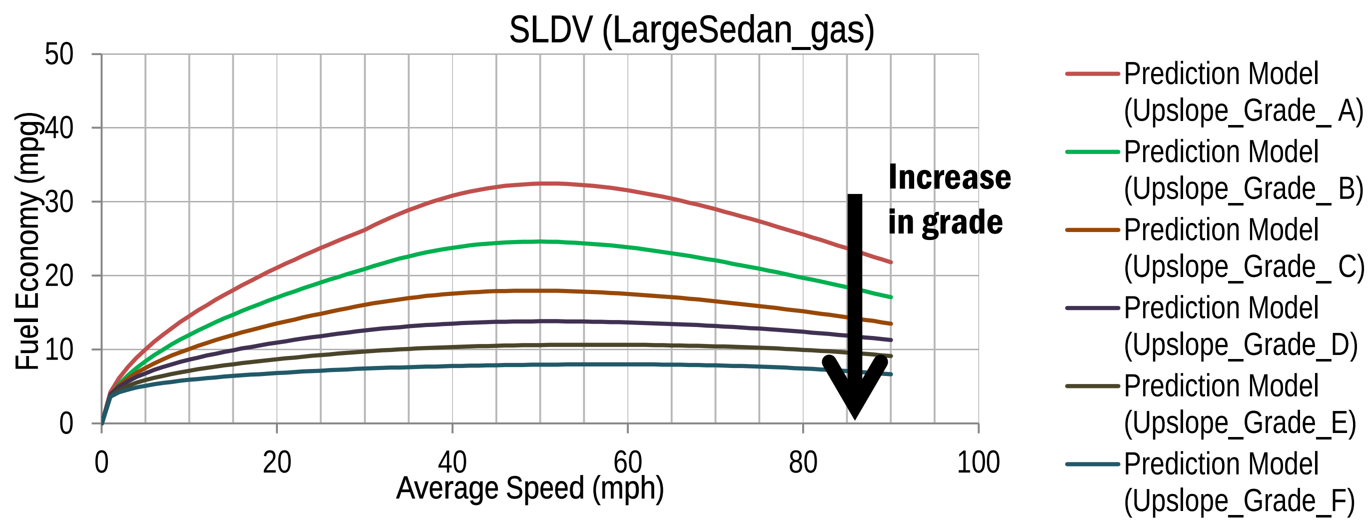
Full Access Control (FAC) – Downslope Grade, Large Sedan, Gasoline

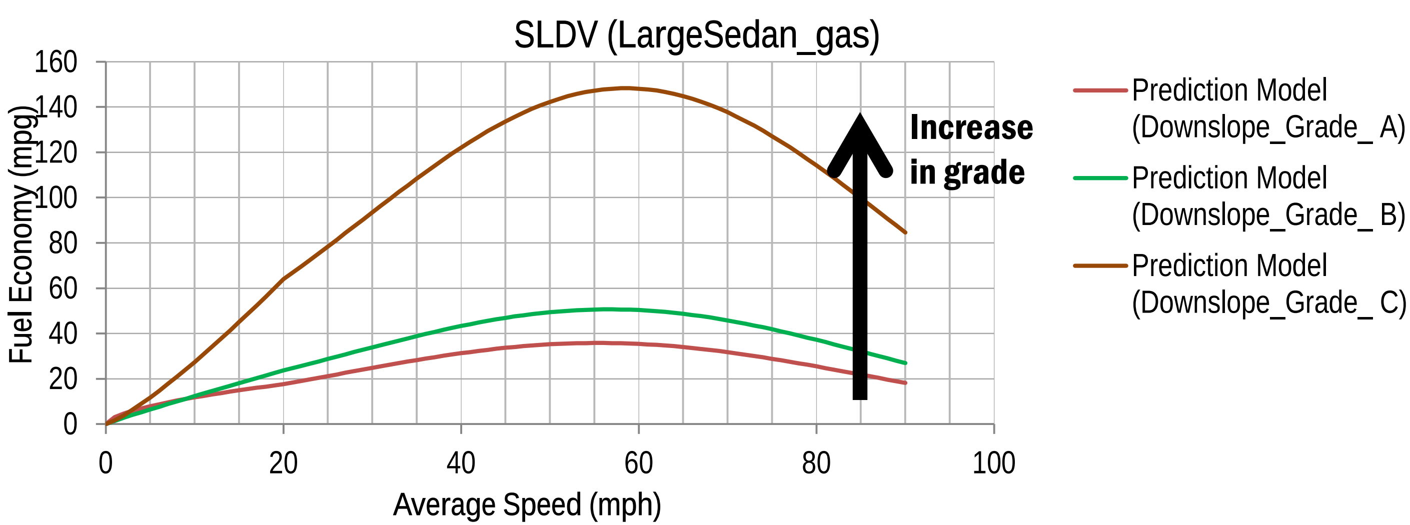




Fuel Economy Prediction Models

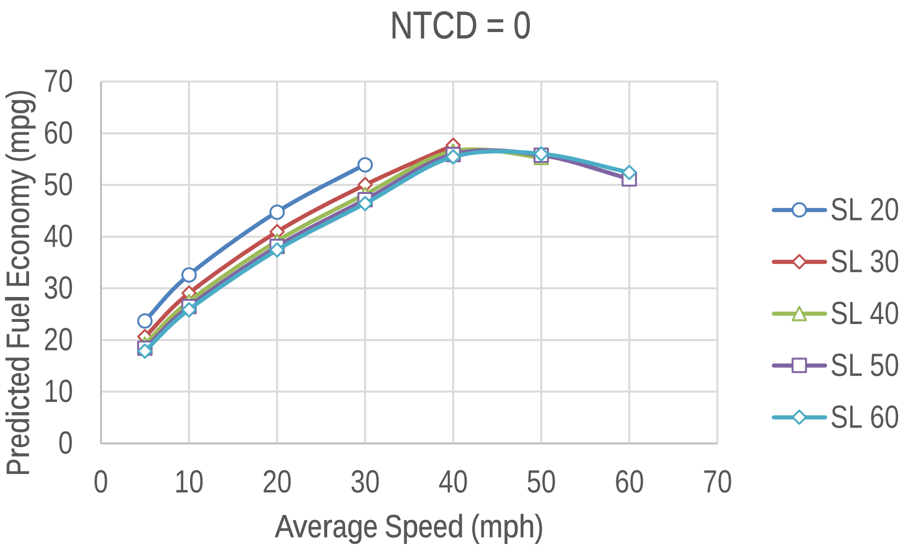
Full Access Control (FAC) – Large Sedan, Gasoline: Upslope vs Downslope Grades

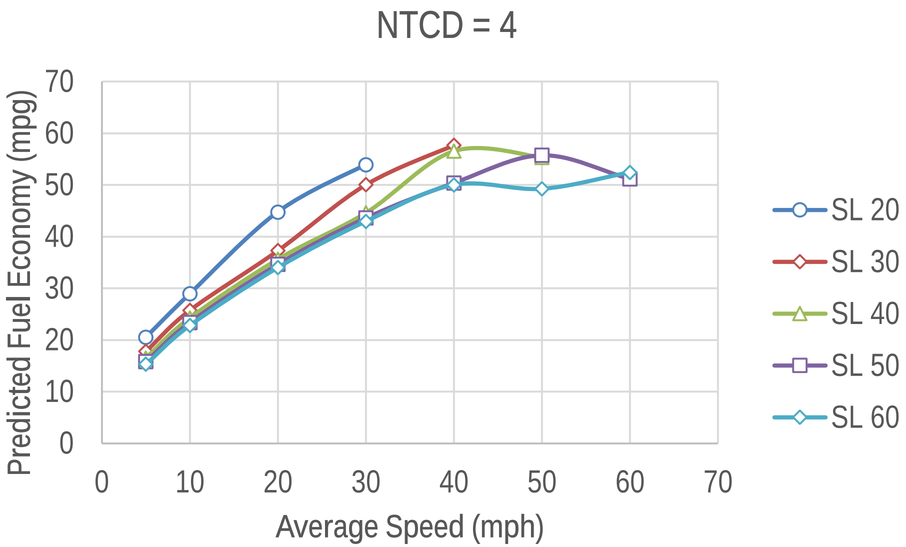




Fuel Consumption Prediction Models

PNAC – Effect of Number of Traffic Control Device (NTCD)

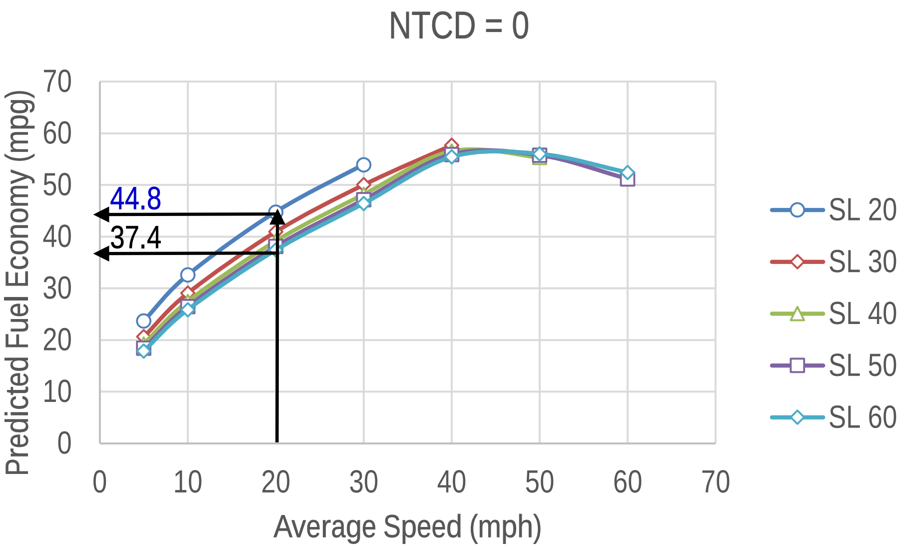


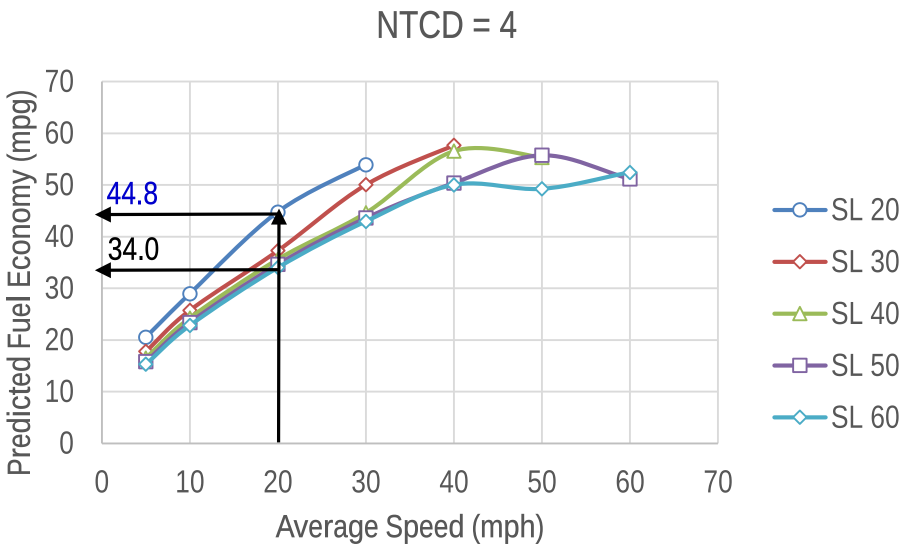


- Effect of NTCD is nil if LOS A (AS/SL >0.85)
- For same AS, with decrease in SL, FE increases => less speed variation
- For same AS and SL, with increase in NTCD, FE decreases

Fuel Consumption Prediction Models

PNAC – Effect of Number of Traffic Control Device (NTCD)



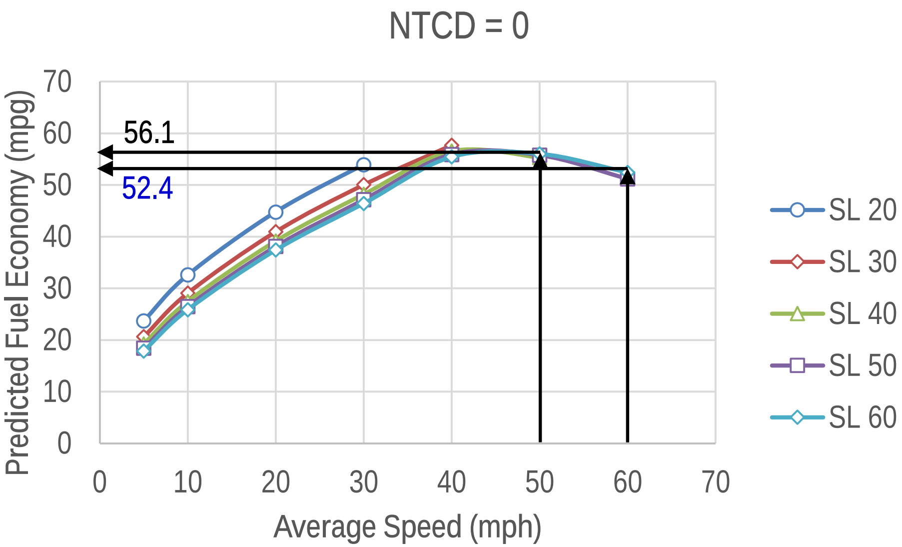


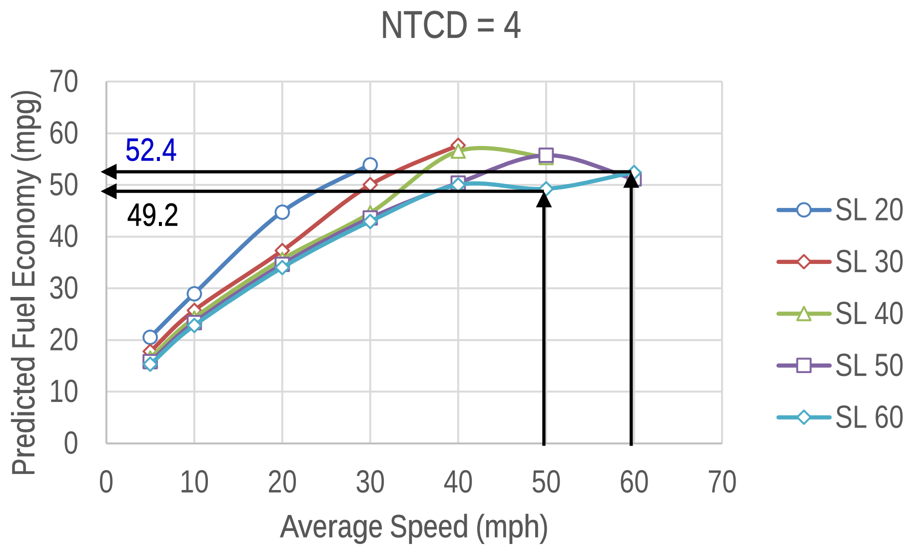
- Effect of NTCD is nil if LOS A (AS/SL >0.85)
- For same AS, with decrease in SL, FE increases => less speed variation
- For same AS and SL, with increase in NTCD, FE decreases

	FE @ 20 mph SL = 20 AS/SL =1	FE @ 20 mph SL = 60 AS/SL = 0.33
NTCD =0	44.8 mpg	37.4 mpg
NTCD =4	44.8 mpg	34.0 mpg

Fuel Consumption Prediction Models

PNAC – Effect of Number of Traffic Control Device (NTCD)





- Effect of NTCD is nil if LOS A (AS/SL >0.85)
- For same AS, with decrease in SL, FE increases => less speed variation
- For same AS and SL, with increase in NTCD, FE decreases

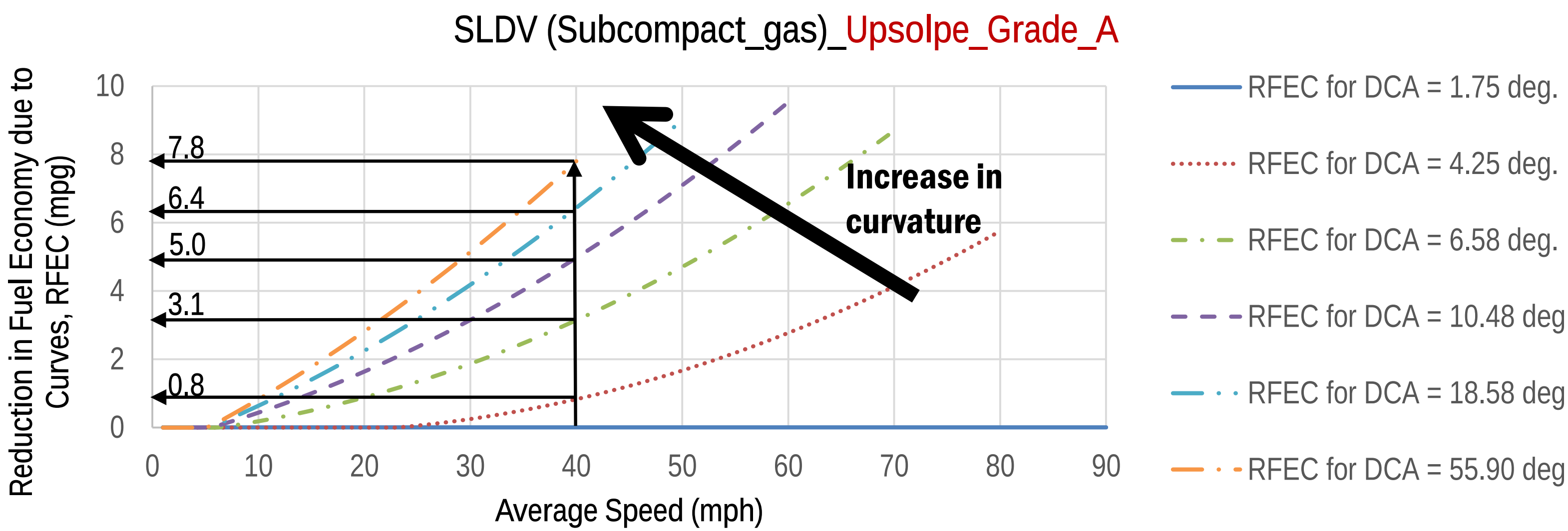
	FE @ 50 mph SL = 60 AS/SL =0.83	FE @ 60 mph SL = 60 AS/SL = 1
NTCD =0	56.1 mpg	52.4 mpg
NTCD =4	49.2 mpg	52.4 mpg

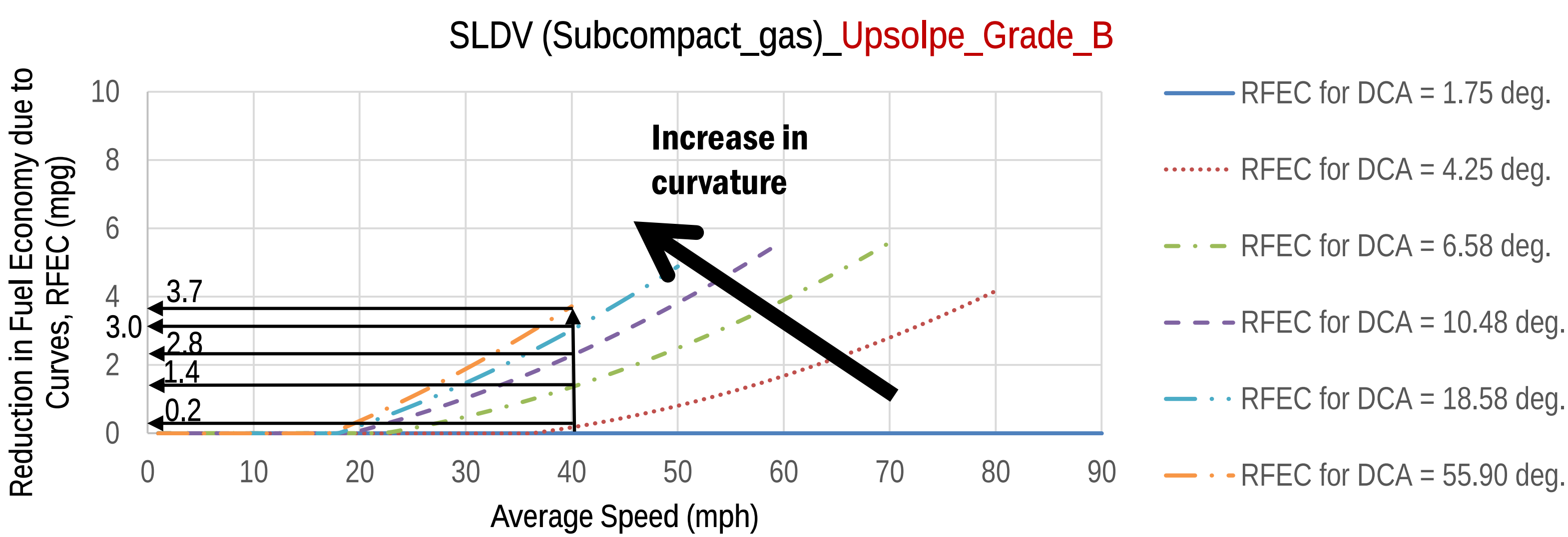
Reduction in Fuel Economy due to Curves (RFEC) Model

- RFEC model is quadratic polynomial function of:
  - Average Speed (AS),
  - Degrees of Curvature (DCA), &
  - Grade Level (GR_{level}).
- Each Curvature level (CR_{level}) has a suggested maximum vehicle average speed.
- RFEC models developed for FAC, PNAC, & for each simulated vehicle separately.
  - RFEC calculated relative to curve level A.
- Increase in fuel consumption due to curve can then be calculated.

Curve Level	Suggested Max Average Speed (mph)
A	90
B	60
C	50
D	45
E	35
F	25

Reduction in Fuel Economy due to Curves (RFEC)
Upslope Grade, Subcompact, Gasoline





Incremental Increase in Fuel Consumption due to Pavement Roughness

- Pavement Condition Adjustment Factors (PCAF) has been developed:

Increase in fuel consumption relative to the fuel consumption on a Good category pavement for each of the roughness levels & vehicle speeds.

- PCAF determined for each of the 30 vehicle models separately as a function of vehicle speed (10-90 mph).

Example: Prediction of Fuel Economy at 45 mph, 6.58° curve, Poor(A) Pavement Condition, & two grades (+0.2% & -1.45%)

		Average Speed: 45 mph || Degree of curvature: 6.58˚ || Grade: +0.2% || Roughness: Poor (A)			Average Speed: 45 mph || Degree of curvature: 6.58˚ || Grade: -1.45% || Roughness: Poor (A)		
		Base Fuel Economy	First Fuel Economy adjustment due to **Roughness**	Second Fuel Economy adjustment due to **Curves**	Base Fuel Economy	First Fuel Economy adjustment due to **Roughness**	Second Fuel Economy adjustment due to **Curves**
Sub-compact	Gas	55.5 mpg	55.1 mpg	53.9 mpg	86.5 mpg	85.9 mpg	82.4 mpg
Midsize Sedan	Gas	40.5 mpg	40.1 mpg	37.7 mpg	62.6 mpg	62.1 mpg	55.8 mpg
Large Sedan	Gas	32.0 mpg	31.8 mpg	31.1 mpg	46.9 mpg	46.6 mpg	45.4 mpg
Large SUV	Gas	20.9 mpg	20.8 mpg	20.6 mpg	31.1 mpg	30.9 mpg	29.5 mpg
Class 2 Truck	Gas	19.4 mpg	19.2 mpg	18.8 mpg	32.3 mpg	31.9 mpg	30.8 mpg

Overall Summary

- Database of synthetically optimized (SO) driving cycles developed.
- Vehicle models developed are robust enough to capture dynamic forces at tire road interface.
- Verification results indicate that the models developed have good fidelity in vehicle response estimation & analysis.
- Range of vehicle powertrain configuration are considered with anticipation of accommodating future technological advances in vehicle development.
- Fuel economy (FE) prediction models developed for 30 vehicles
  - Smooth straight roads with grades
  - Smooth roads with curvatures & grades
  - Straight roads with a range of roughness levels & zero grade

Thank you…

- References

  - Hajj, E., Xu, H., Bailey, G., Sime, M., Chkaiban, R., Kazemi, S.-F., Sebaaly, P. E. (in press). *Phase I: Modeling the Relationship Between Vehicle Speed and Fuel Consumption* (pp. 135p.). Washington, DC: U.S. Department of Transportation; Federal Highway Administration.
  - Hajj, E., Chkaiban, R., Bailey, G., Sime, M., Xu, H., Sebaaly, P. E. (in press). *Task 8a. - b: The Effects of Road Curvatures on Fuel Consumption* (pp. 116p.). Washington, DC: U.S. Department of Transportation; Federal Highway Administration.
  - Sime, M., Bailey, G., Hajj, E., Chkaiban, R., Sebaaly, P. E. (under review). *Task 9a. - b: Incremental Fuel Consumption Due to Pavement Roughness* (pp. 34p.). Washington, DC: U.S. Department of Transportation; Federal Highway Administration.

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