Integration of a Lean NOx Trap Model and an Engine map into PSAT

May 1, 2007
10th DOE CLEERS workshop
University of Michigan, Dearborn, MI

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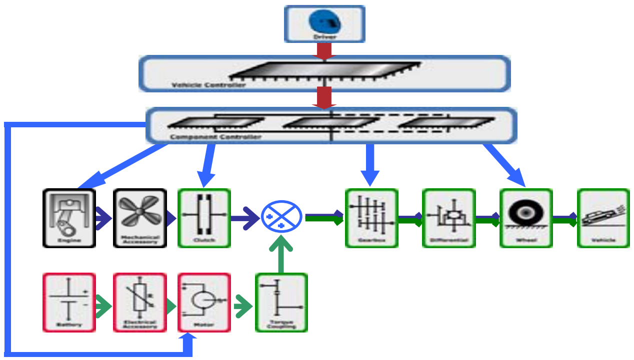
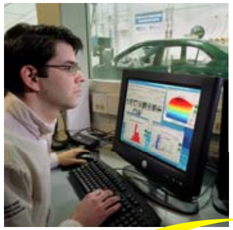
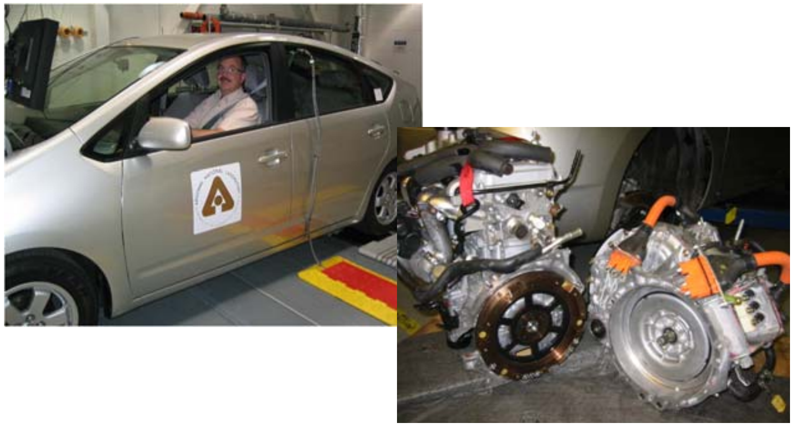
Argonne National Laboratory

Kalyana Chakravarthy, Zhiming Gao, Stuart Daw & Johney Green
OakRidge National Laboratory

ANL Capabilities Designed for Vehicle Systems Analysis







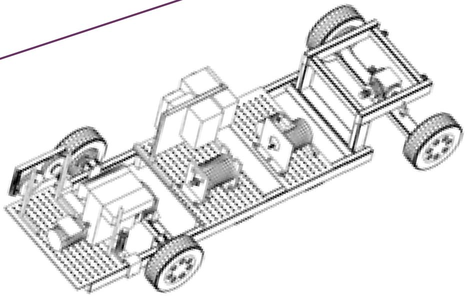
Simulation

Validation

Emulation

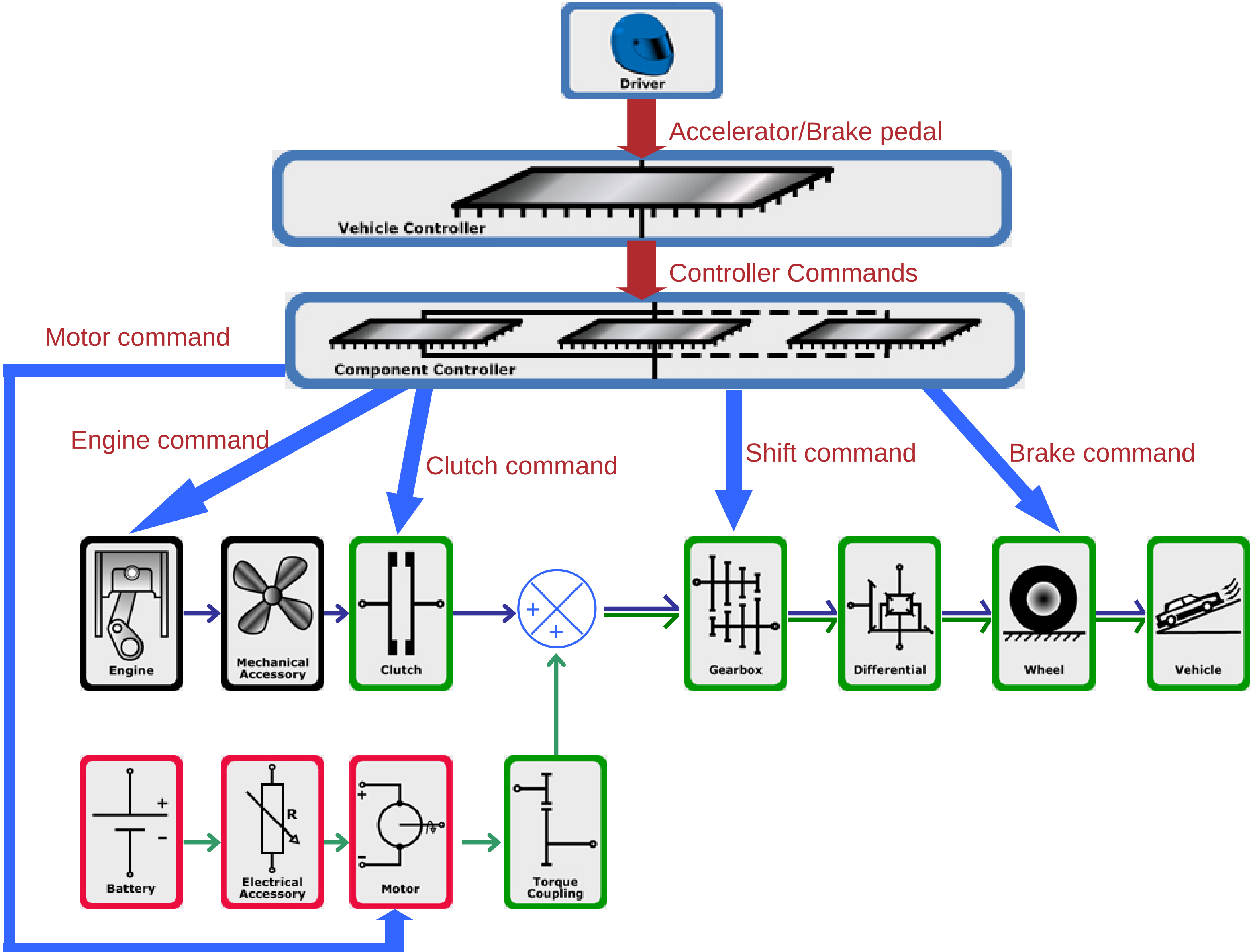
Modeling and Simulation (PSAT)

Benchmarking & Validation



Component/System Emulation Using Hardware-In-the-Loop (HIL)

Forward Modeling Provides Accurate Results



PSAT Simulations Support R&D and Management Decisions

- After a thorough assessment, PSAT has been selected in 2004 as the primary vehicle model for all FreedomCAR and 21 CTP activities by the U.S.DOE, stating that "*All future code development and enhancements for OFCVT shall focus on PSAT and PSAT-PRO*"

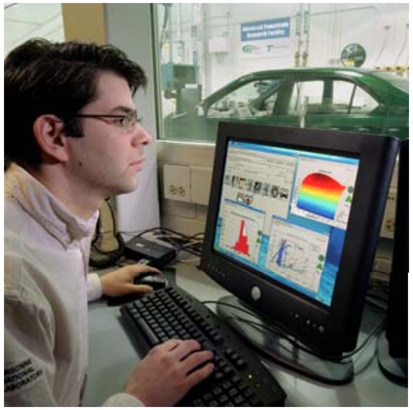
- PSAT has been awarded a R&D100 Award in 2004 represented to the 100 most technologically significant new products and processes introduced into the market each year.

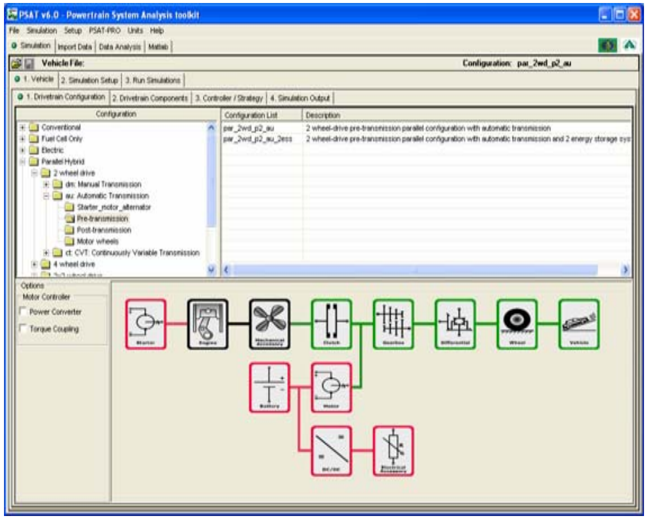
- PSAT has been awarded a Technology Transfer Award in 2007

- *"… We need a model that's intuitive, easy to use, and provides accurate results. PSAT gives us that."* Randy Yost - GM Engineering Specialist

Developed to meet the requirements of automotive engineering throughout the development process

- Forward-looking model
- Wide range of vehicle applications from light to heavy duty
- Unrivaled number of predefined configurations
- Easy implementation of proprietary data, component models, control strategies or drive cycles
- Easy to use Graphical User Interface
- Possibility to use the control strategies for Hardware-in-the-Loop / Software-in-the-Loop
- Designed for co-simulation environment





Different Users Have Different Needs

U.S.DOE

- Validated complete vehicle models
- Focused on fuel economy and performance
- Evaluate component in vehicle system context
- Evaluate fuel economy potential of future technologies (e.g. goals)

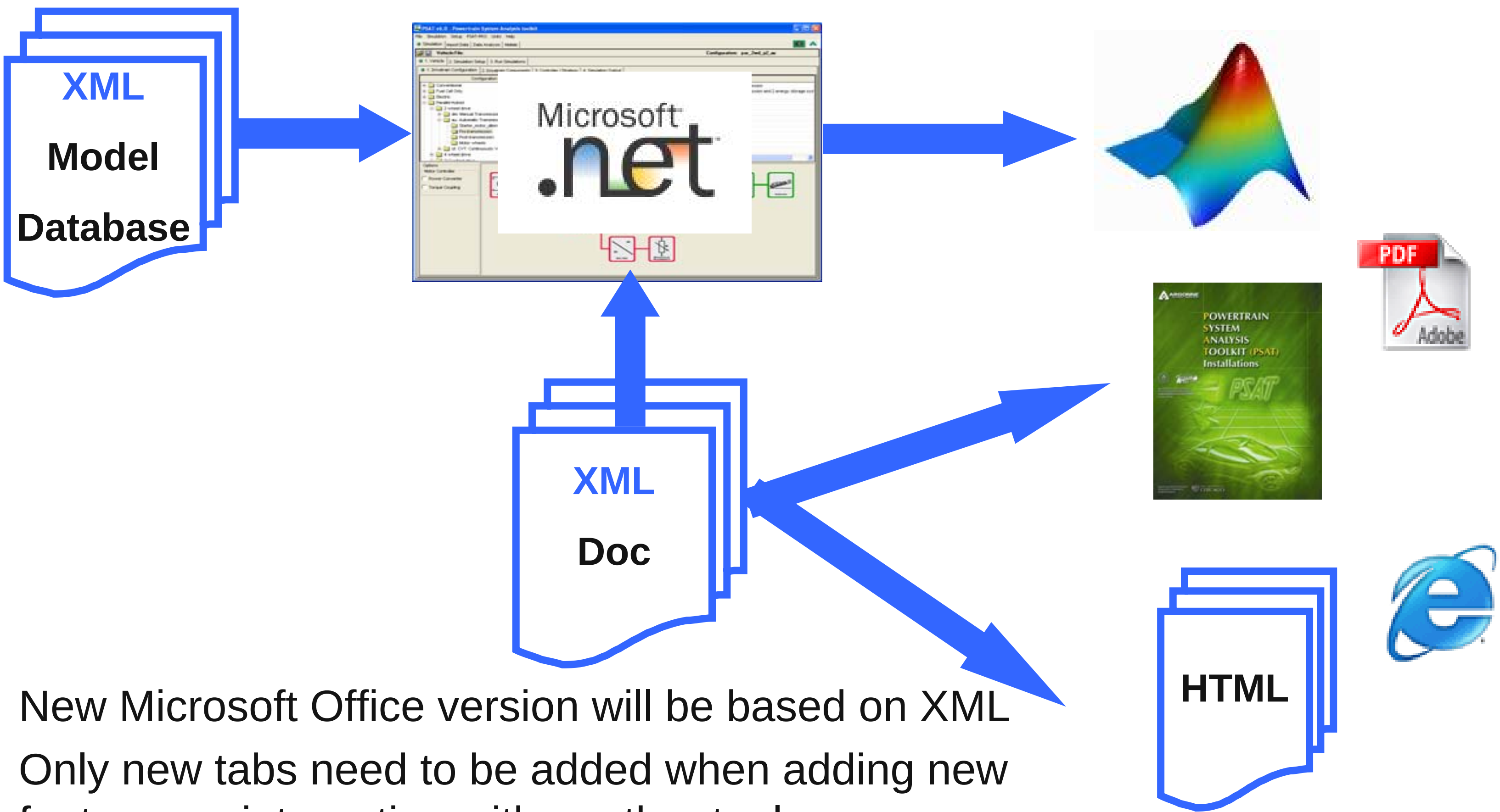
Car Companies

- Implement their own models/data/controls
- Also interested in drive quality & emissions
- Need to have different levels of modeling
- Interested in software architecture & post-processing tools

Suppliers

- Implement their component model / subsystems (reuse rest of PSAT models)
- Interested in software architecture & post-processing tools

PSAT Architecture Designed to Suit All Users Needs

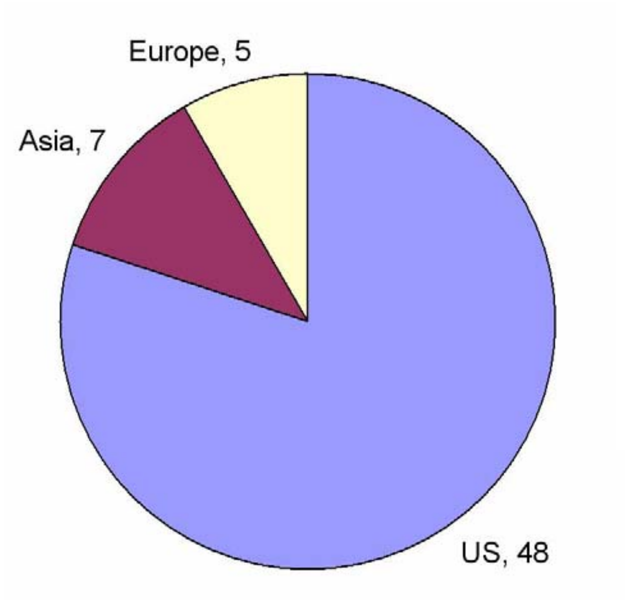


- New Microsoft Office version will be based on XML
- Only new tabs need to be added when adding new features or integrating with another tool

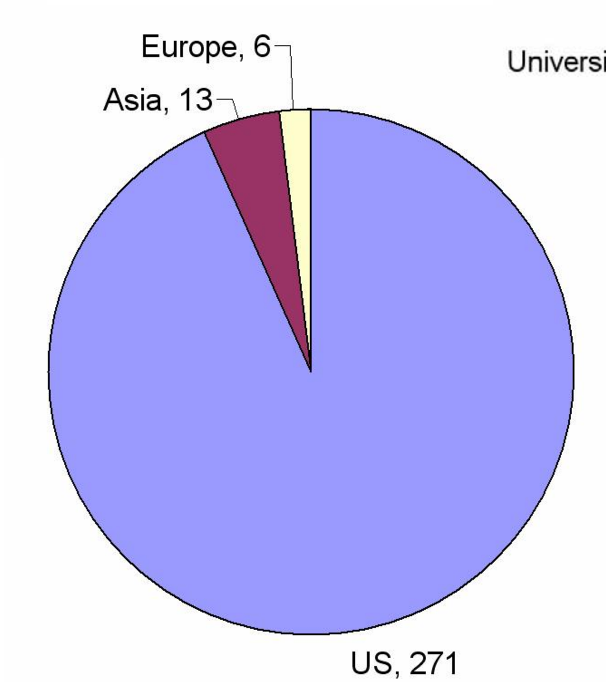
Large User Database Continuously Increasing

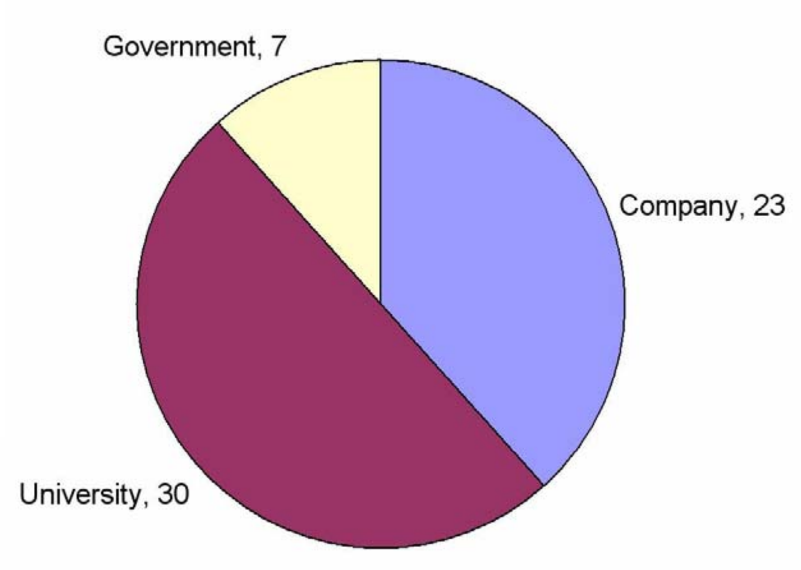
CATARC

Numerous US Companies are Using PSAT



Licenses Location Favors US





Licenses Distribution Evenly Split

PSAT Close to 300 Users

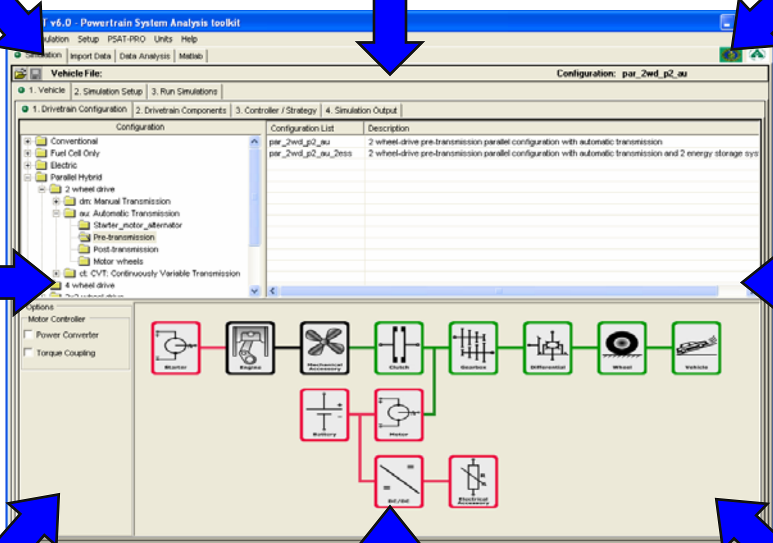
As of December 2006

PSAT - A Single Tool Throughout the Development Process

Build and compare large number of powertrain configurations

Easy selection of data, models, control strategies or drive cycles

Run batch mode



Ensure simulation traceability

Analyze and compare test and simulation data

Easy implementation of data, models, control strategies or drive cycles

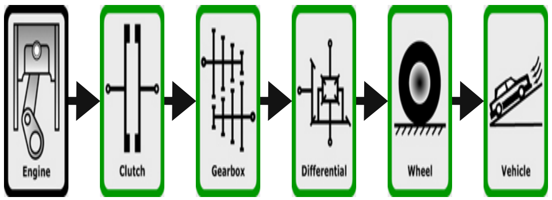
Ensure model compatibilities

Use models and controls for HIL/RCP

Large Number of Configurations Achieved Through Automatic Building

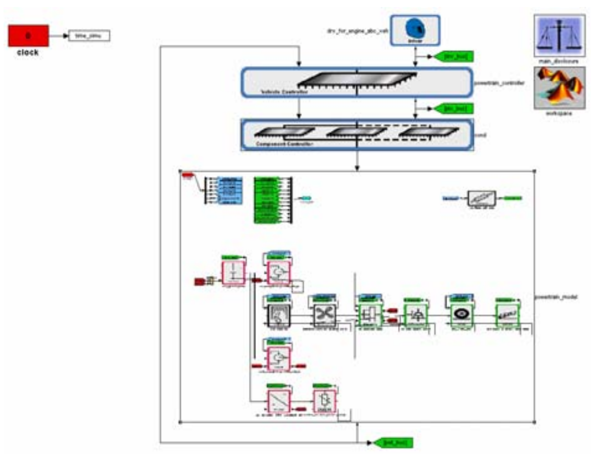
Option #1

Drag & Drop



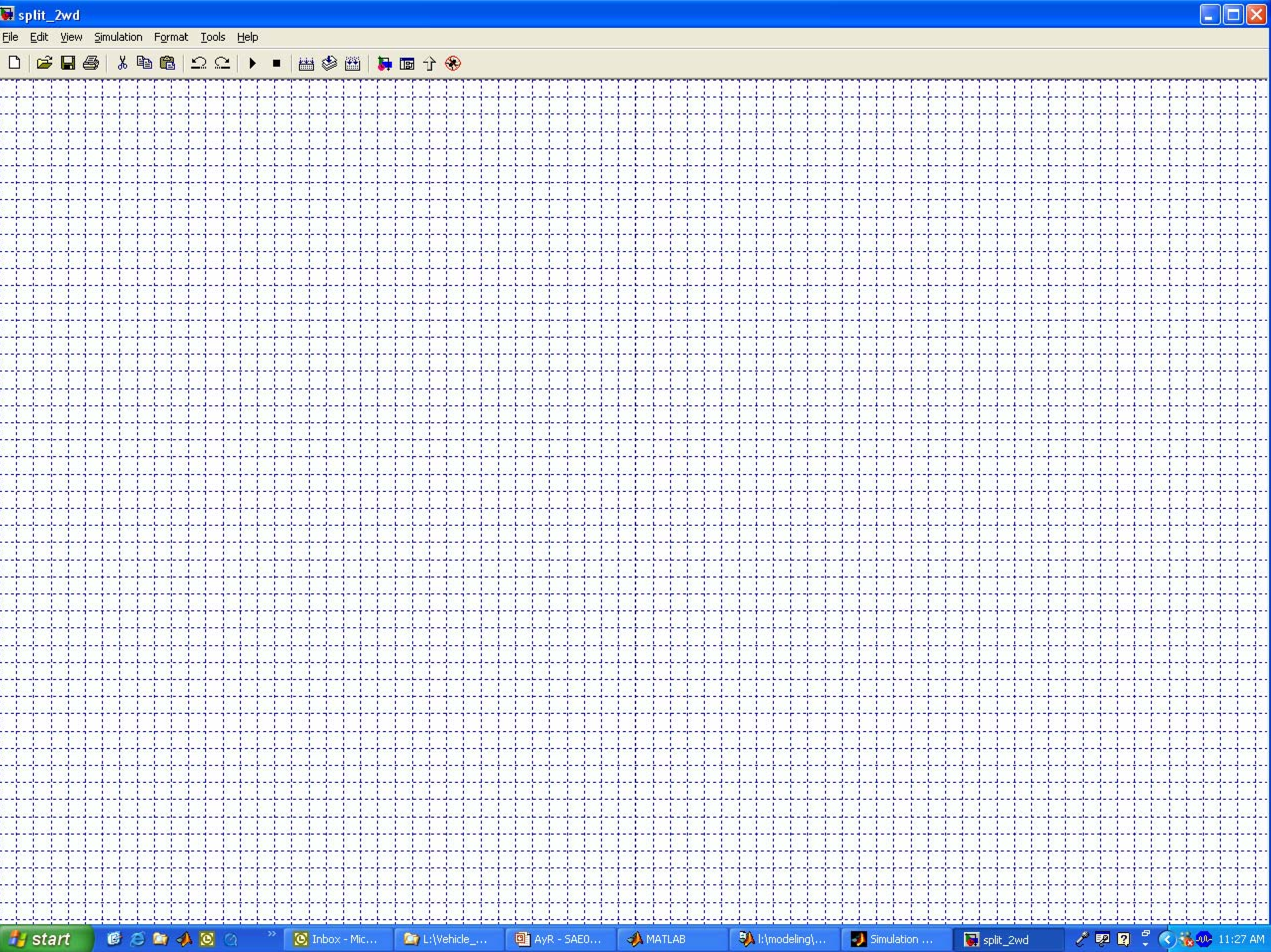
Option #2

Save Entire Vehicles



Solution

Build model based on users choices using add_block & add_line


split_2wd
File
Edit
View
Simulation
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Inbox - Mic...
L:\Vehicle_...
AyR - SAE0...
MATLAB
I:\modeling\...
Simulation ...
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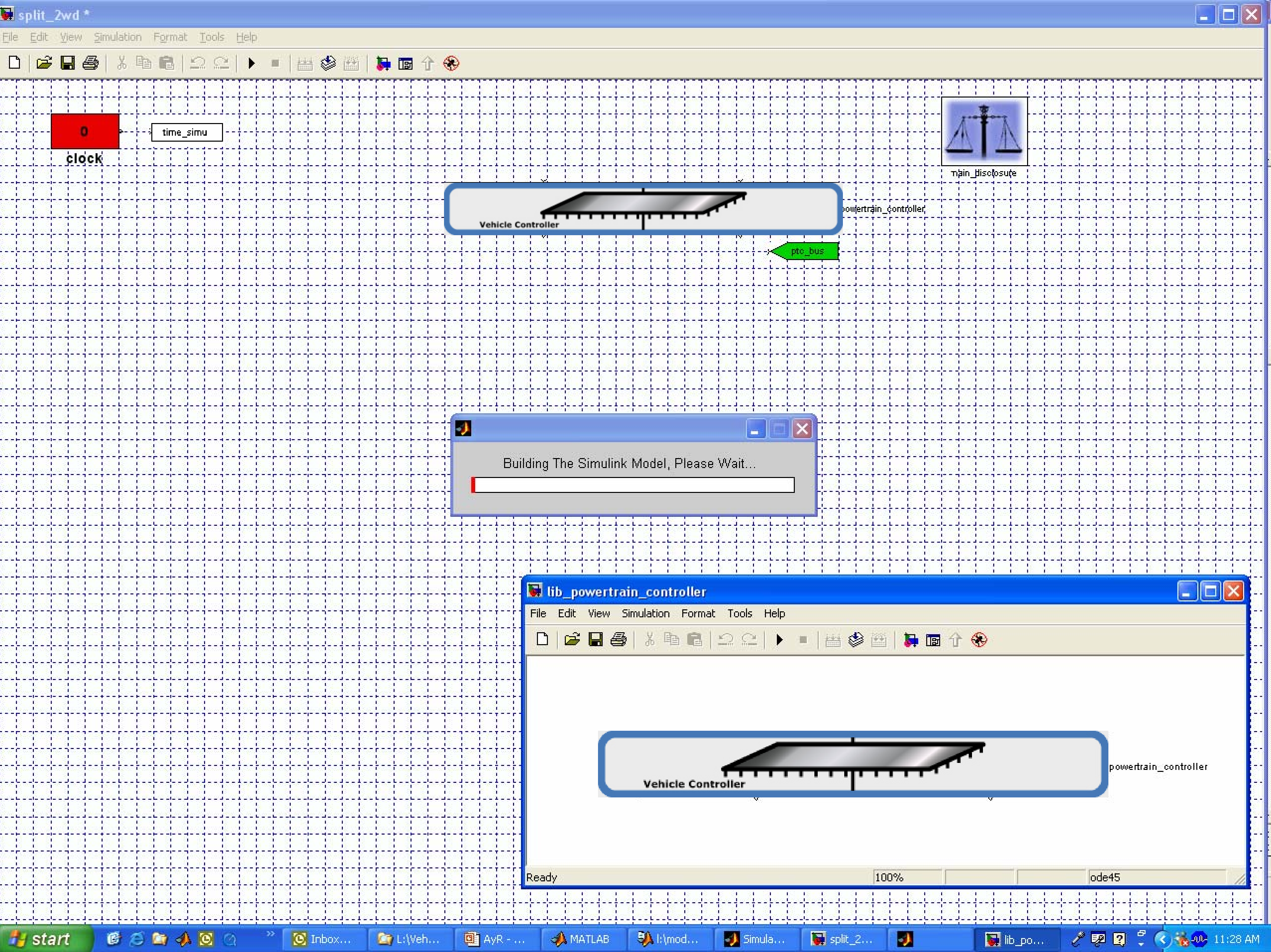
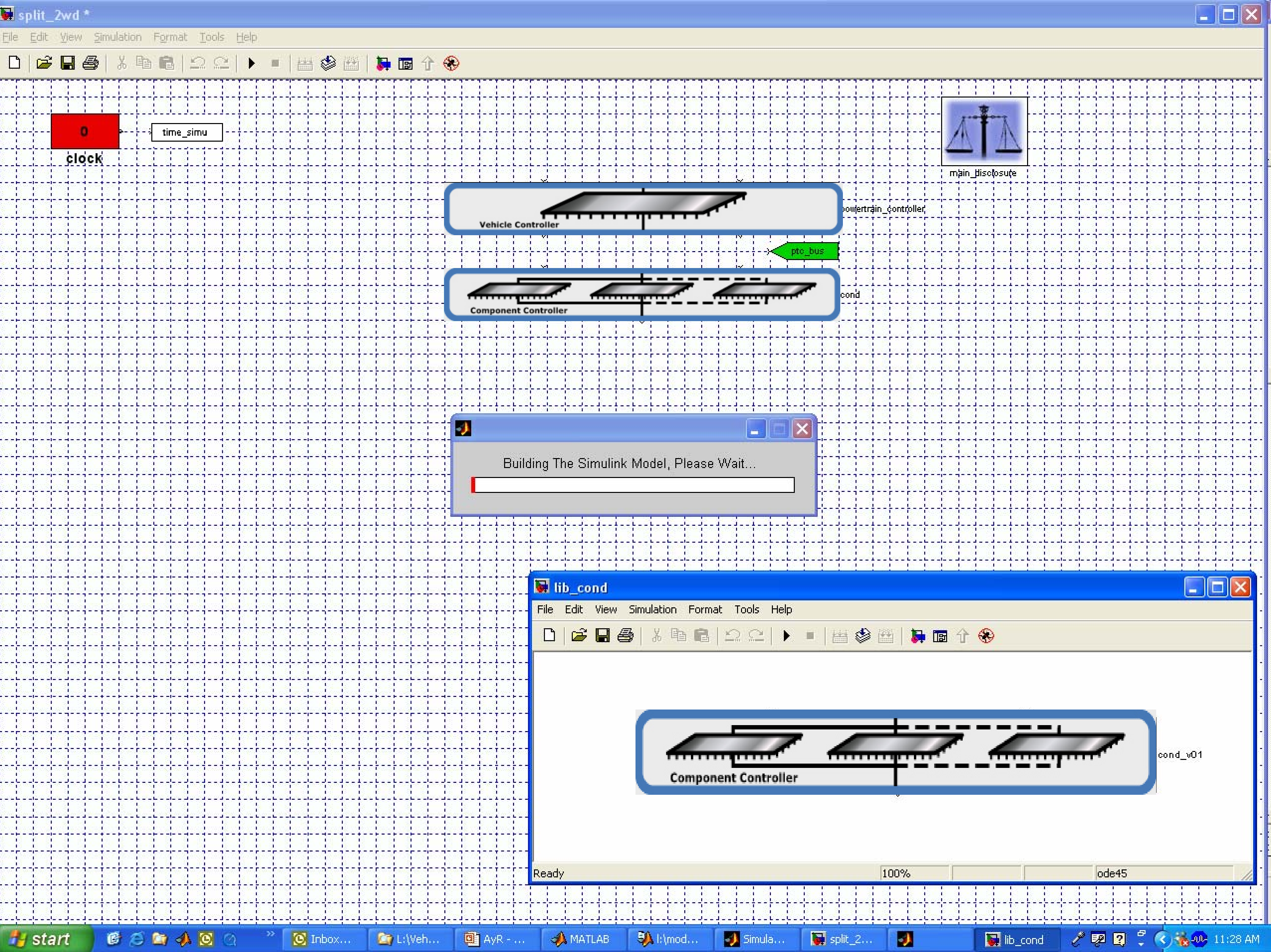
11:27 AM


split_2wd *
File Edit View Simulation Format Tools Help
0
clock
time_simu
main_disclosure
Vehicle Controller
powertrain_controller
ptc_bus
Building The Simulink Model, Please Wait...
lib_powertrain_controller
File Edit View Simulation Format Tools Help
Vehicle Controller
powertrain_controller
Ready
100%
ode45
start
11:28 AM



split_2wd *
File Edit View Simulation Format Tools Help
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Vehicle Controller
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Component Controller
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Building The Simulink Model, Please Wait...
lib_cond
File Edit View Simulation Format Tools Help
Component Controller
cond_v01
Ready
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Inbox...
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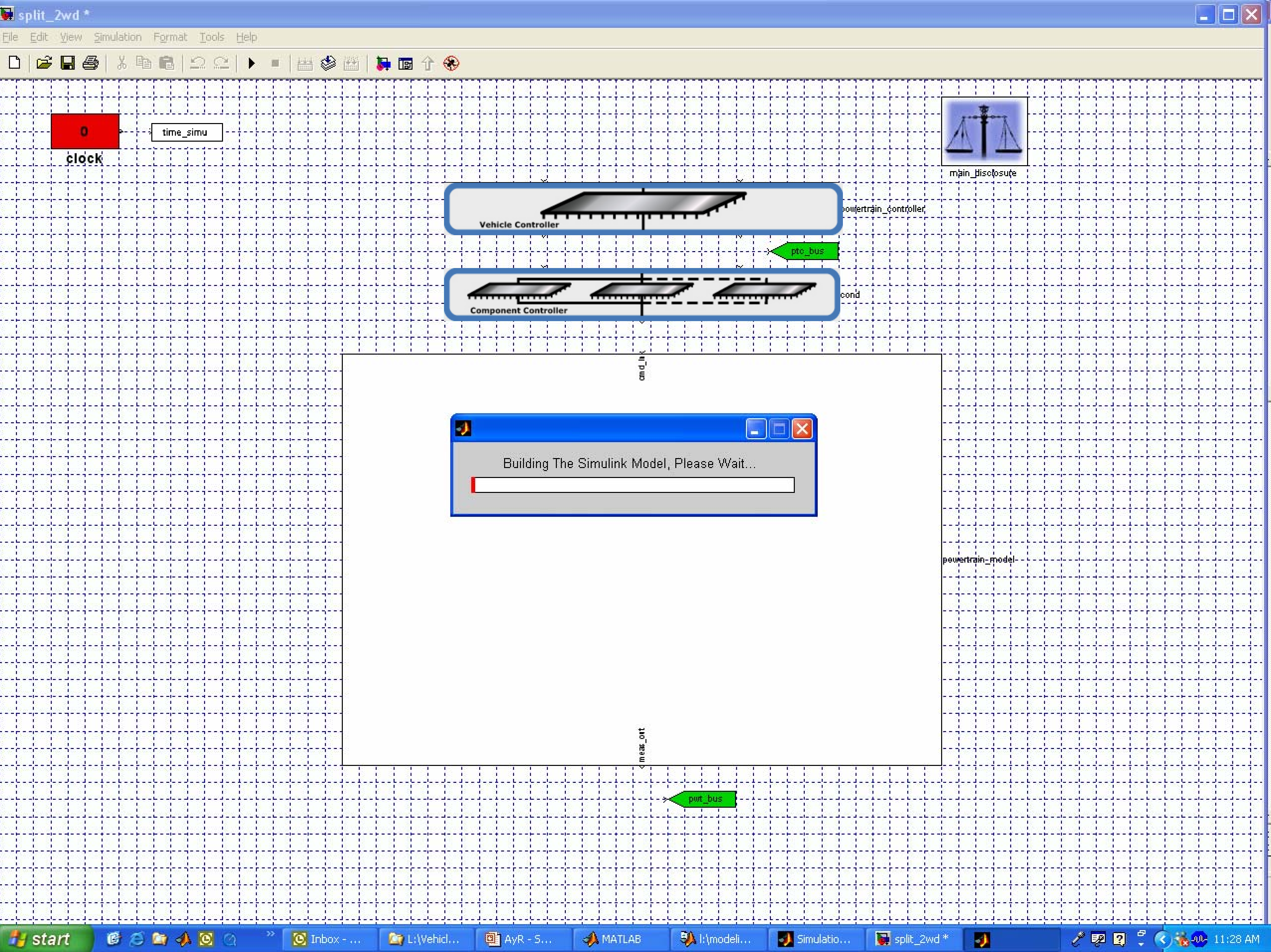
split_2...
lib_cond
11:28 AM


split_2wd *
File Edit View Simulation Format Tools Help
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Vehicle Controller
powertrain_controller
ptc_bus
Component Controller
cond
cmd_in
Building The Simulink Model, Please Wait...
powertrain_model
meas_out
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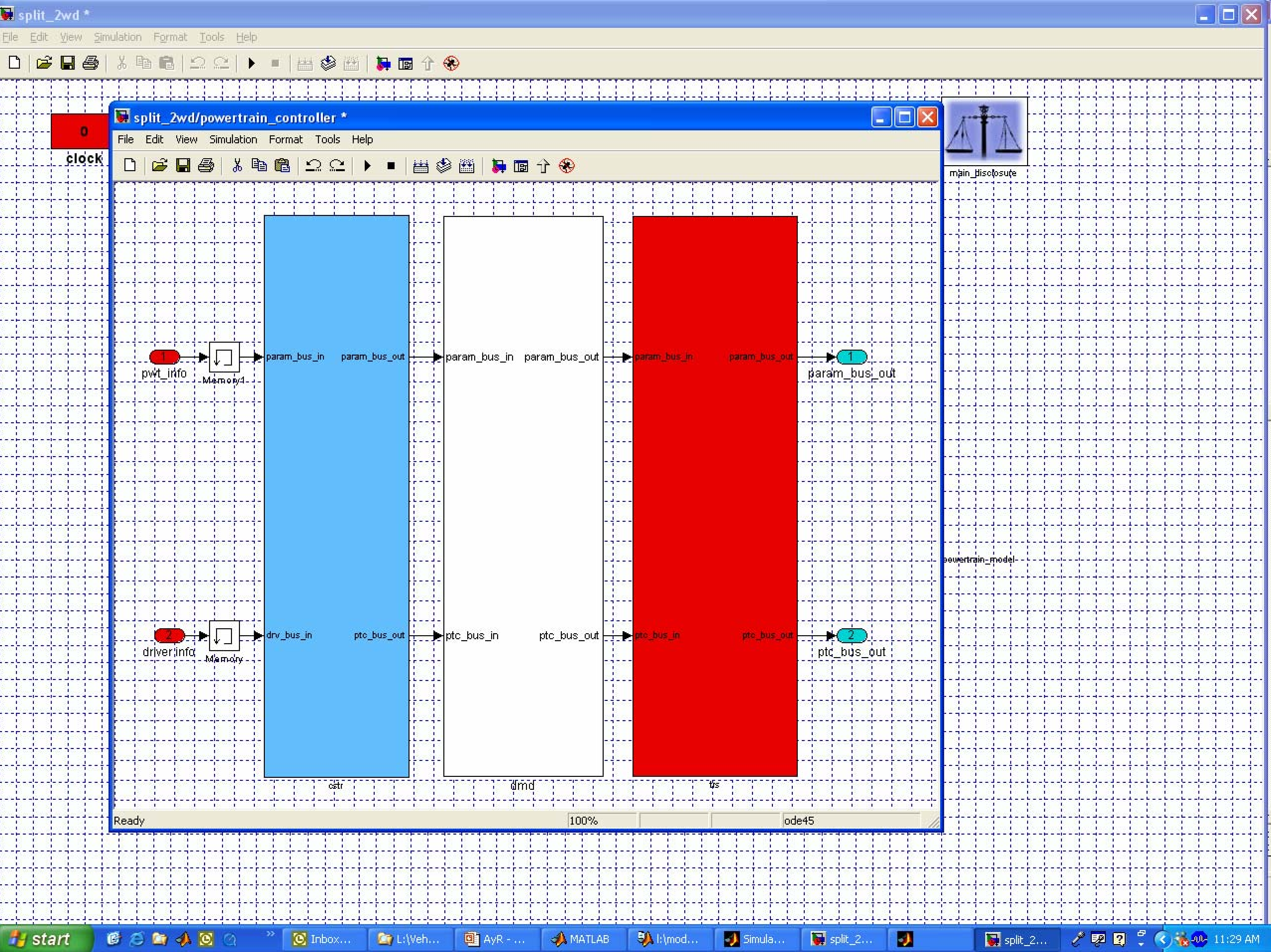
split_2wd *
11:28 AM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Memory1
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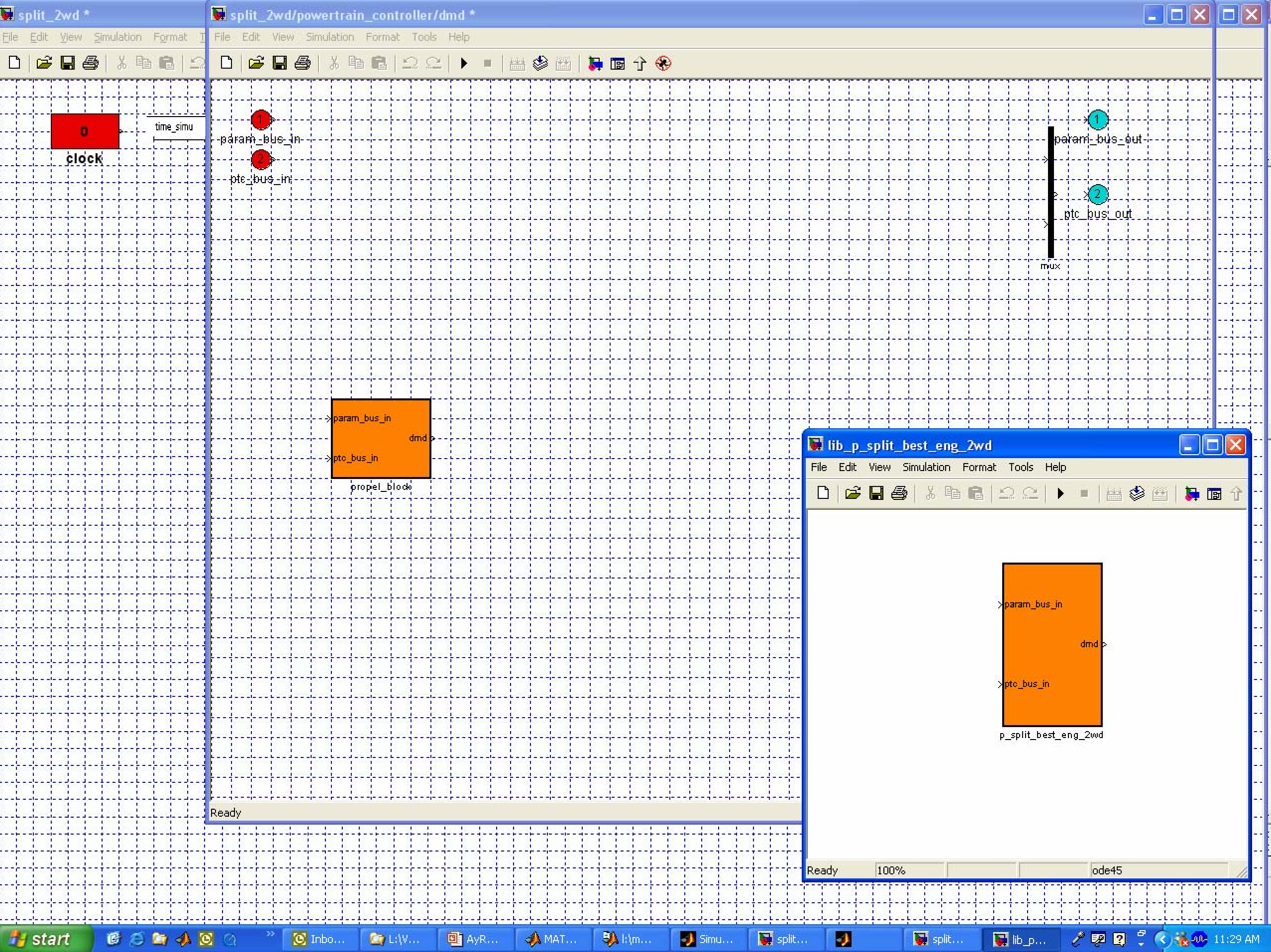
param_bus_out
param_bus_out
driver info
Memory
drv_bus_in
ptc_bus_out
ptc_bus_in
ptc_bus_out
cstr
dmd
powertrain_model
Ready
100%
ode45
start
MATLAB
11:29 AM


split_2wd *
split_2wd/powertrain_controller/dmd *
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2
ptc_bus_in
1
param_bus_out
2
ptc_bus_out
mux
param_bus_in
dmd
ptc_bus_in
propel_block
Ready
lib_p_split_best_eng_2wd
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param_bus_in
dmd
ptc_bus_in
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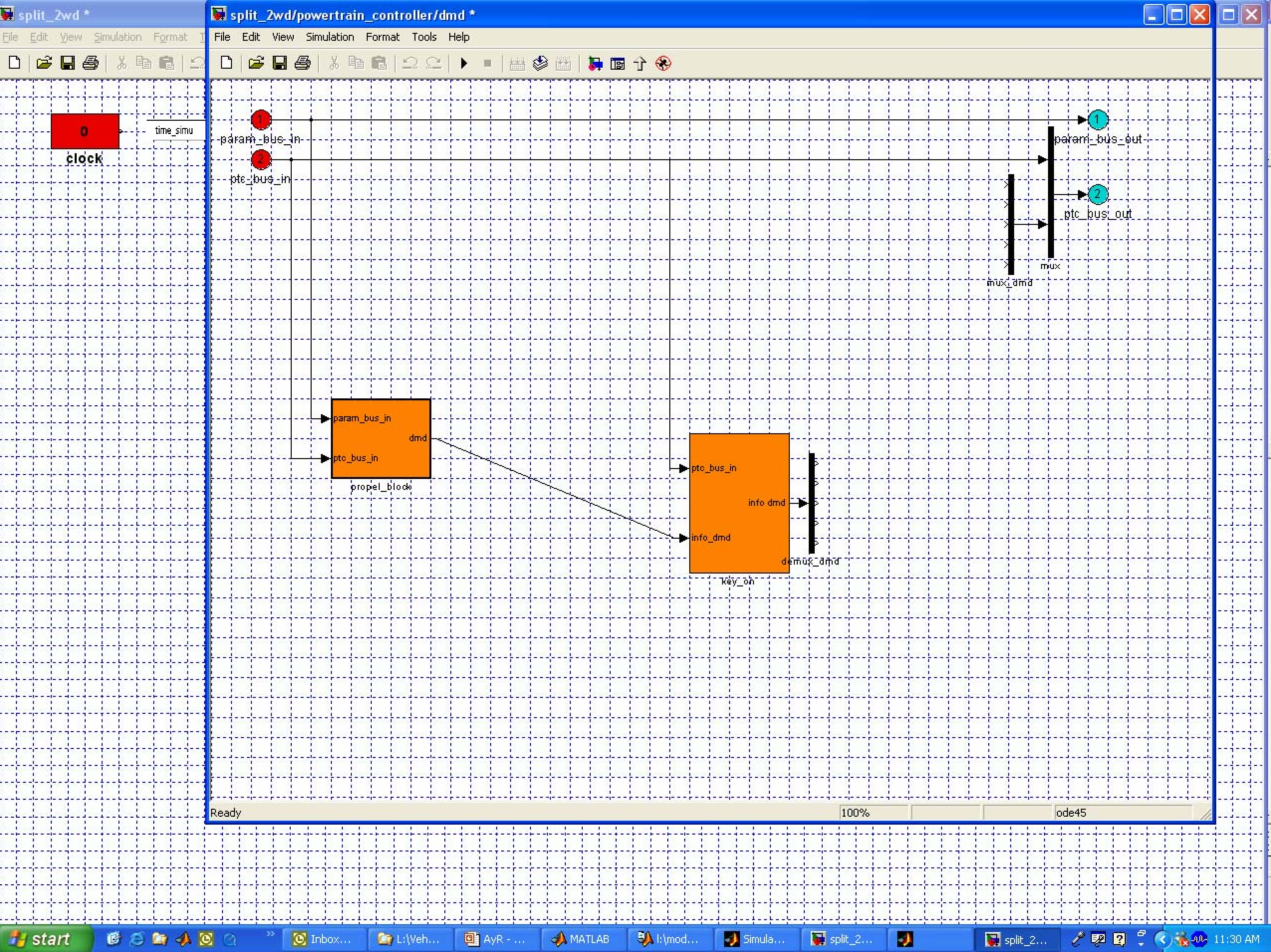
Ready 100% ode45
start
11:29 AM


split_2wd *
split_2wd/powertrain_controller/dmd *
File Edit View Simulation Format Tools Help
0
clock
time_simu
param_bus_in
ptc_bus_in
param_bus_out
ptc_bus_out
mux_dmd
mux
param_bus_in
ptc_bus_in
dmd
propel_block
ptc_bus_in
info dmd
info_dmd
demux_dmd
key_on
Ready
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split_2...
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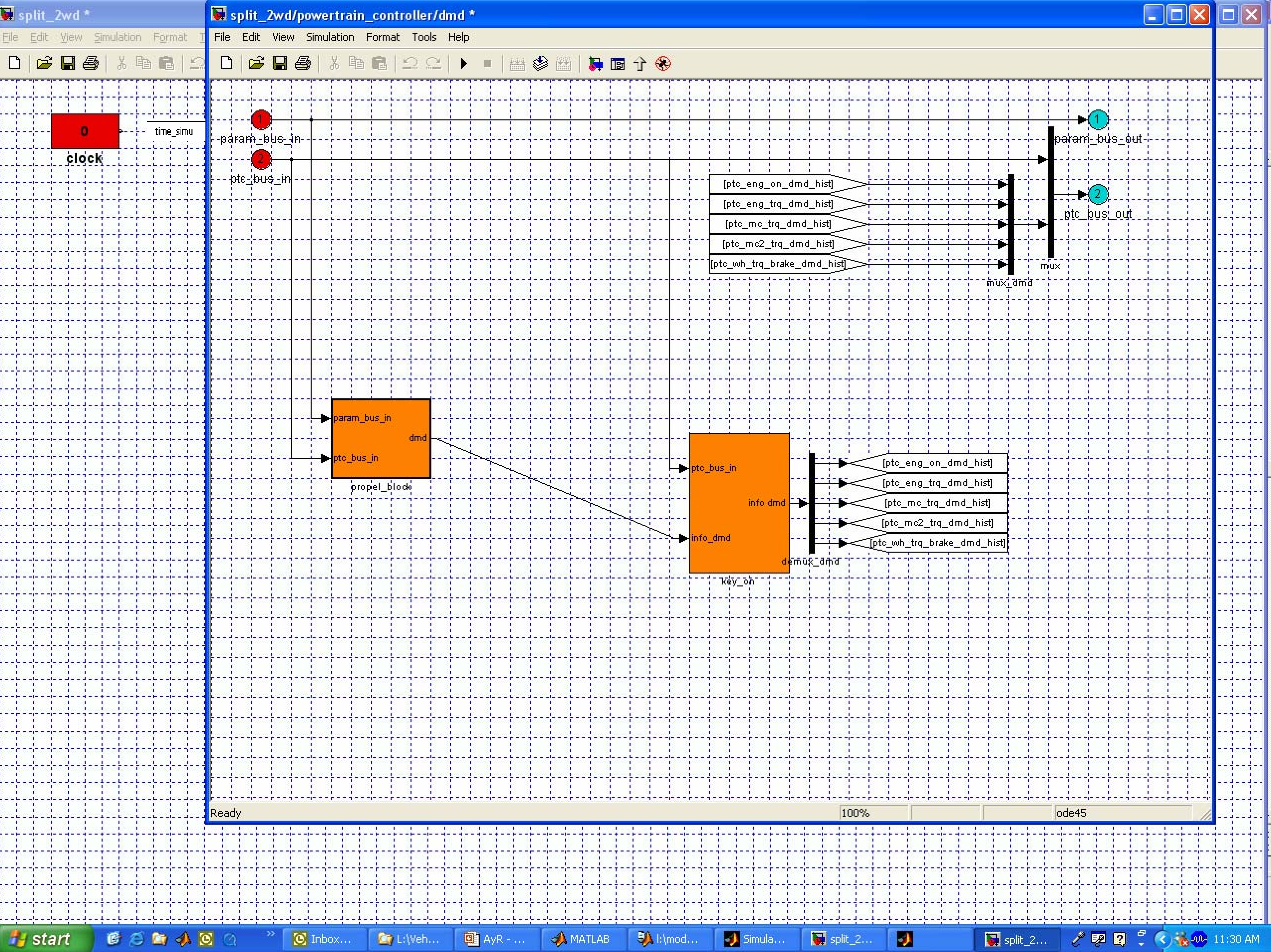

split_2wd/powertrain_controller/dmd *
File Edit View Simulation Format Tools Help
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time_simu
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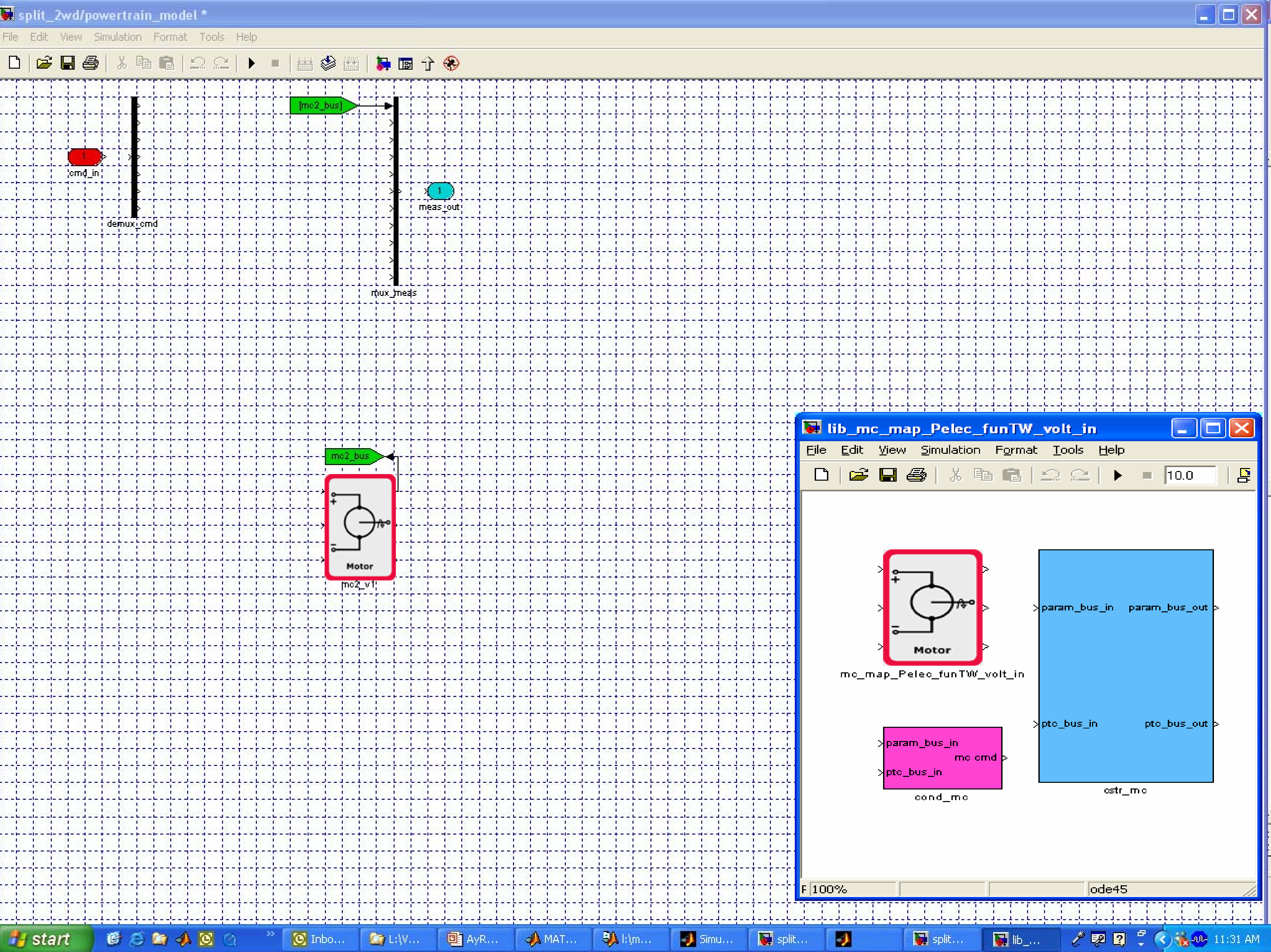
ptc_bus_in
param_bus_out
ptc_bus_out
[ptc_eng_on_dmd_hist]
[ptc_eng_trq_dmd_hist]
[ptc_mc_trq_dmd_hist]
[ptc_mc2_trq_dmd_hist]
[ptc_wh_trq_brake_dmd_hist]
mux_dmd
mux
propel_block
dmd
ptc_bus_in
info dmd
info_dmd
key_on
demux_dmd
Ready
100%
ode45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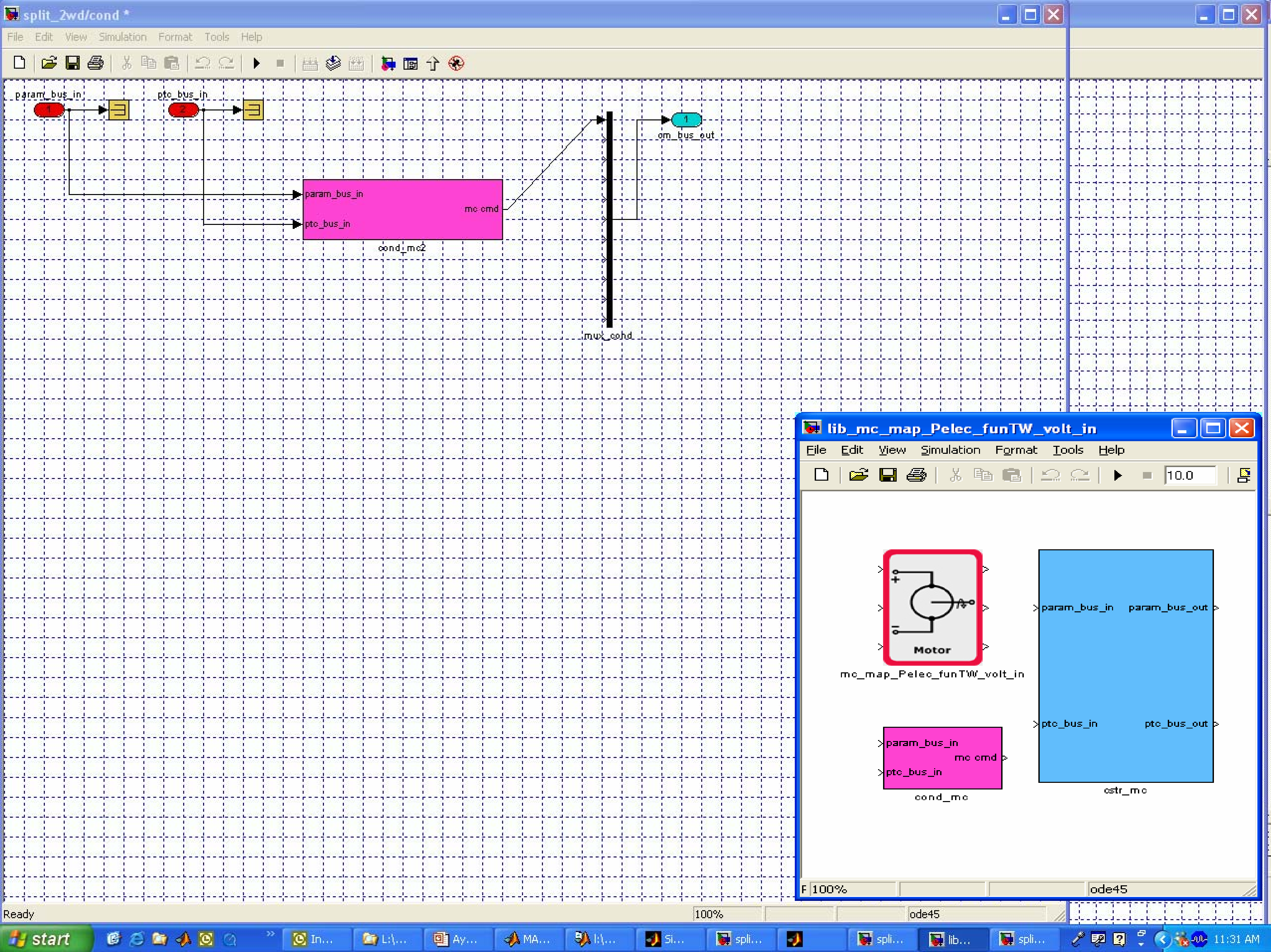
cmd_in
demux_cmd
meas_out
mux_meas
mc2_bus
Motor
mc2_v1
lib_mc_map_Pelec_funTW_volt_in
File Edit View Simulation Format Tools Help
10.0
Motor
mc_map_Pelec_funTW_volt_in
param_bus_in
param_bus_out
ptc_bus_in
ptc_bus_out
cstr_mc
param_bus_in
mc cmd
ptc_bus_in
cond_mc
100%
ode45
start
11:31 AM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File Edit View Simulation Format Tools Help
param_bus_in
ptc_bus_in
param_bus_in
mc cmd
ptc_bus_in
cond_mc2
mux_cond
cm_bus_out
Ready
100%
ode45
lib_mc_map_Pelec_funTW_volt_in
File Edit View Simulation Format Tools Help
10.0
Motor
mc_map_Pelec_funTW_volt_in
param_bus_in
param_bus_out
ptc_bus_in
ptc_bus_out
cstr_mc
param_bus_in
mc cmd
ptc_bus_in
cond_mc
100%
ode45
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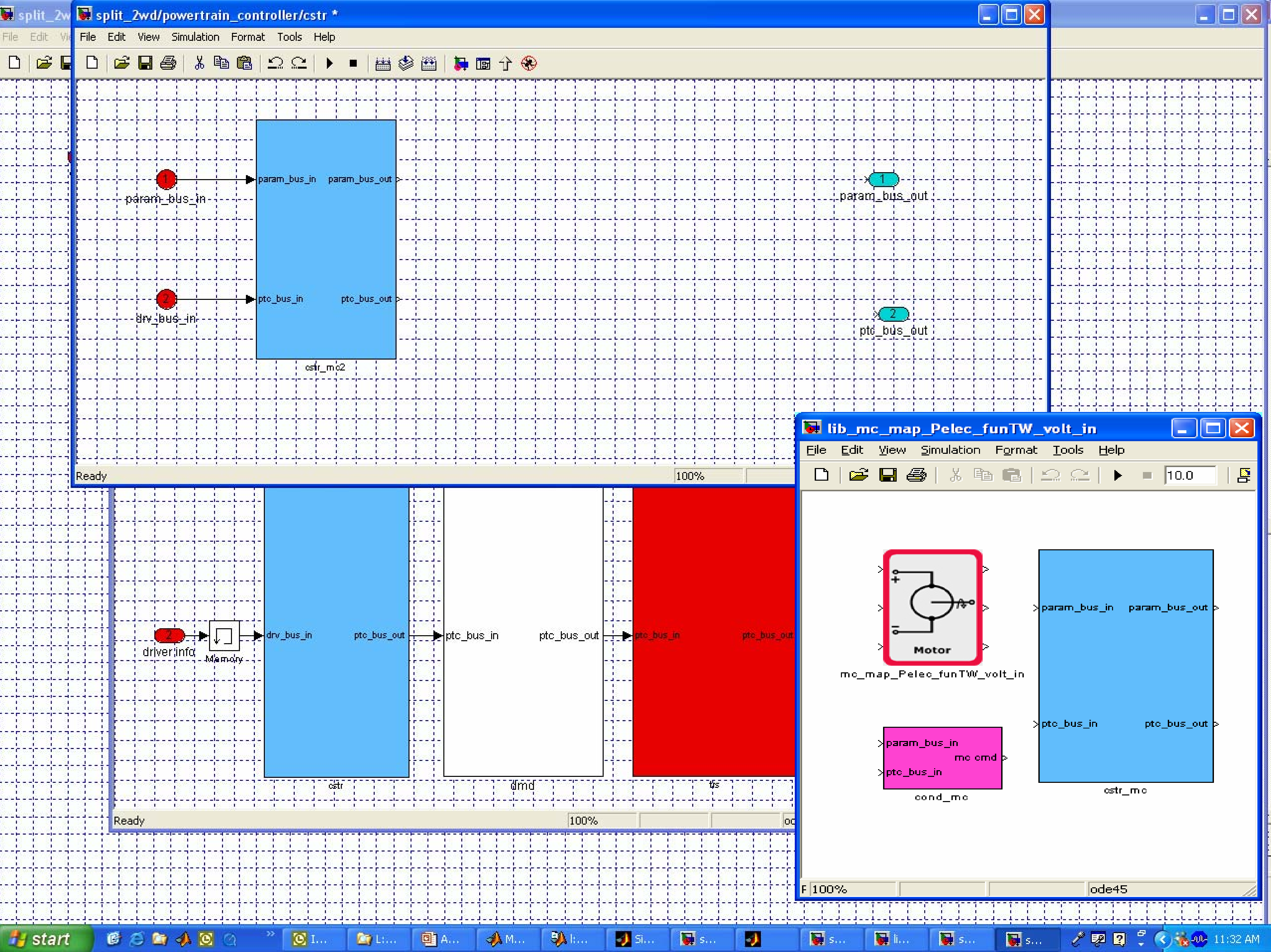
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param_bus_in
param_bus_out
ptc_bus_in
ptc_bus_out
drv_bus_in
cstr_mc2
Ready
100%
drv_bus_in
driver info
Memory
cstr
dmd
lib_mc_map_Pelec_funTW_volt_in
File Edit View Simulation Format Tools Help
10.0
Motor
mc_map_Pelec_funTW_volt_in
mc cmd
cond_mc
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ode45
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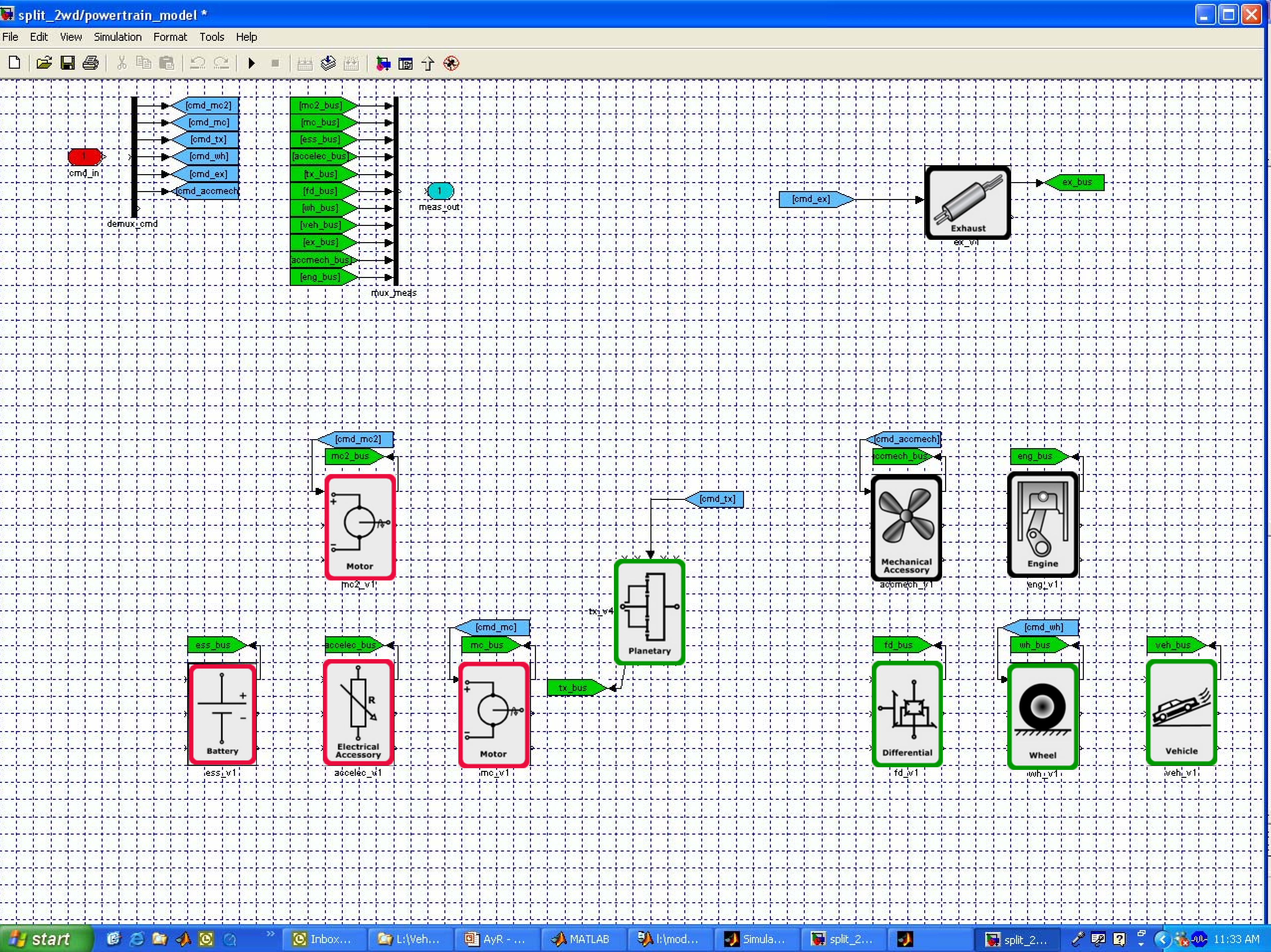
split_2wd/powertrain_model *
File
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Simulation
Format
Tools
Help
cmd_in
demux_cmd
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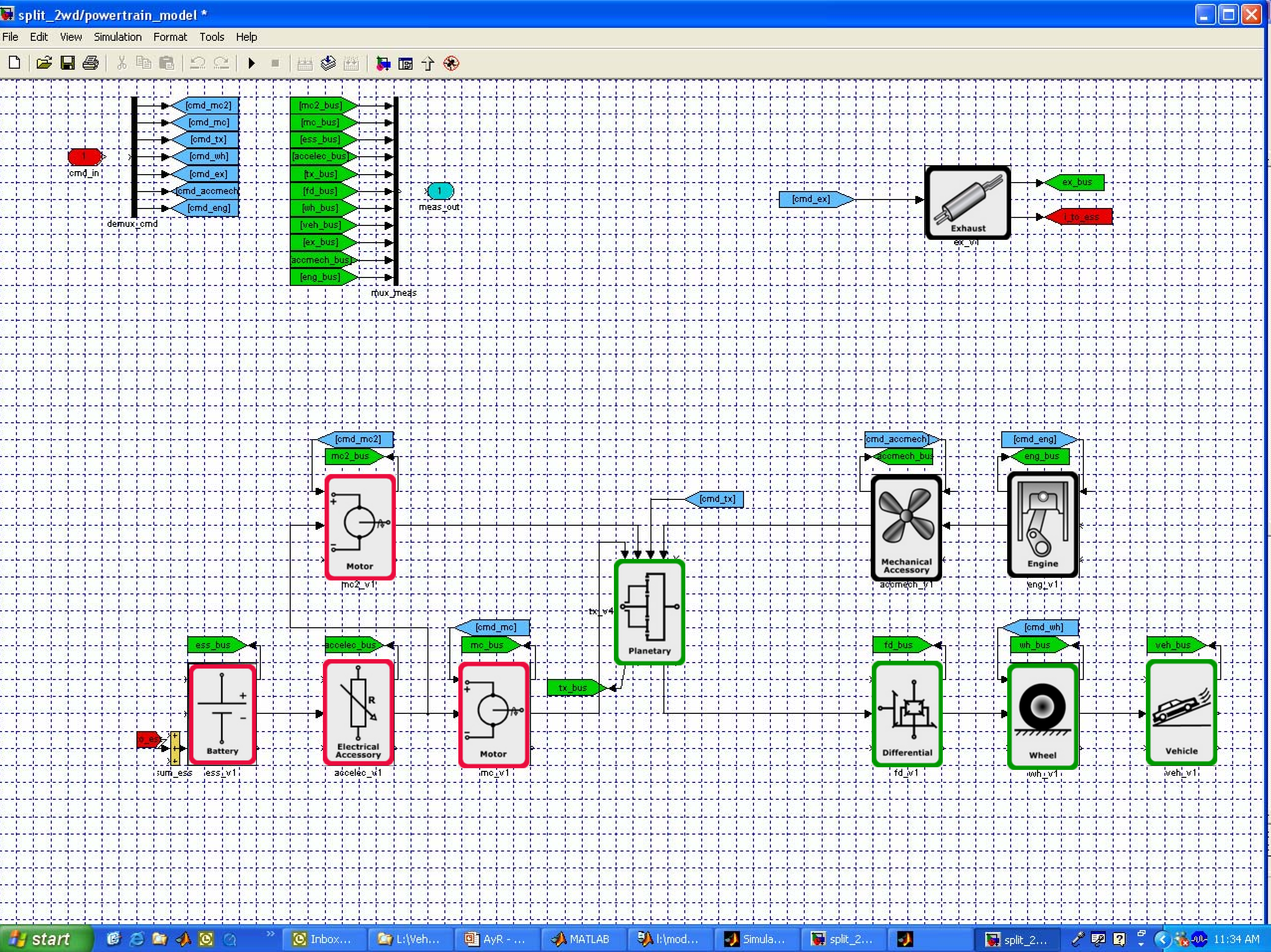
[cmd_mc]
[cmd_tx]
[cmd_wh]
[cmd_ex]
[cmd_accmech]
[mc2_bus]
[mc_bus]
[ess_bus]
[accelec_bus]
[tx_bus]
[fd_bus]
[wh_bus]
[veh_bus]
[ex_bus]
[accmech_bus]
[eng_bus]
mux_meas
meas_out
[cmd_ex]
Exhaust
ex_bus
Motor
mc2_v1
mc2_bus
[cmd_tx]
Planetary
tx_v4
tx_bus
[cmd_accmech]
Mechanical Accessory
accmech_v1
eng_bus
Engine
eng_v1
ess_bus
Battery
ess_v1
accelec_bus
Electrical Accessory
accelec_v1
[cmd_mc]
mc_bus
Motor
mc_v1
fd_bus
Differential
fd_v1
[cmd_wh]
wh_bus
Wheel
wh_v1
veh_bus
Vehicle
veh_v1
start
MATLAB
11:33 AM



split_2wd/powertrain_model *
File Edit View Simulation Format Tools Help
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mc2_bus
Mechanical Accessory
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accmech_bus
Engine
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Motor
mc_v1
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Differential
fd_v1
fd_bus
Wheel
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wh_bus
Vehicle
veh_v1
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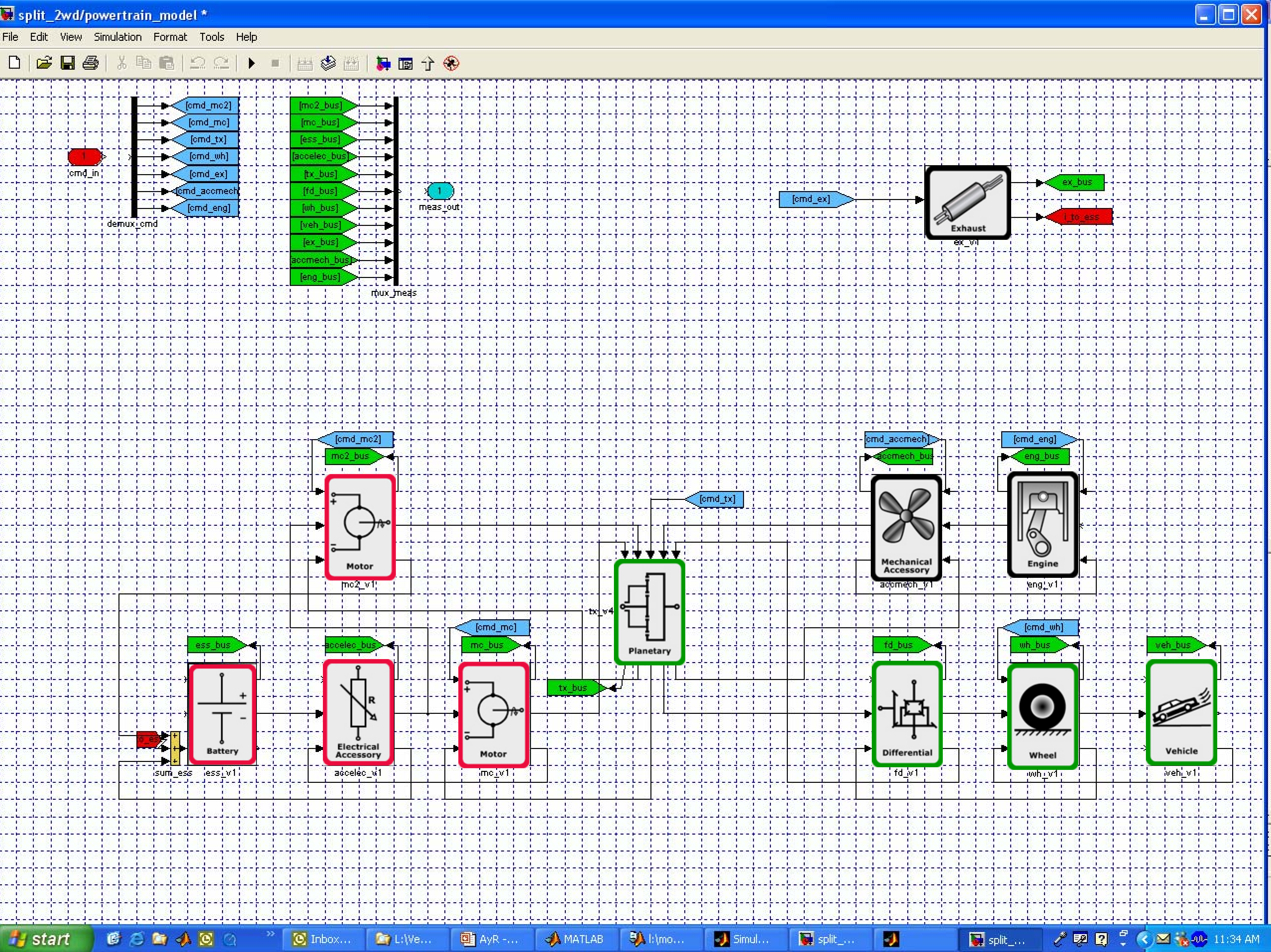
split_2...
split_2...
11:34 AM



split_2wd/powertrain_model *
File Edit View Simulation Format Tools Help
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mux_meas
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Exhaust
ex_v1
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Motor
mc2_v1
tx_v4
Planetary
accmech_bus
Mechanical Accessory
accmech_v1
eng_bus
Engine
eng_v1
ess_bus
Battery
ess_v1
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accelec_bus
Electrical Accessory
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mc_bus
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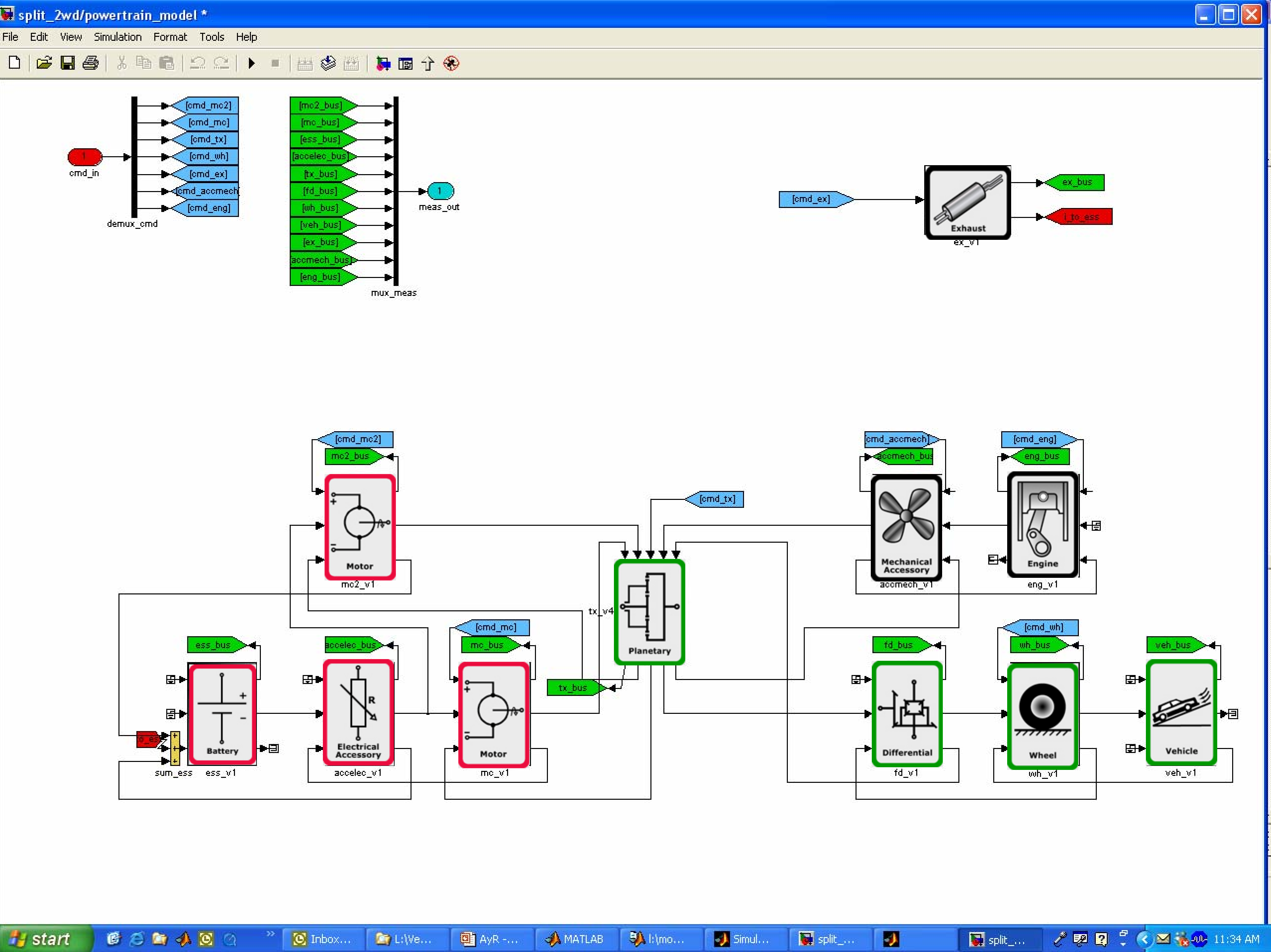

split_2wd/powertrain_model *
File Edit View Simulation Format Tools Help
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mux_meas
meas_out
Exhaust
ex_v1
ex_bus
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Motor
mc2_v1
mc2_bus
Mechanical Accessory
accmech_v1
accmech_bus
Engine
eng_v1
eng_bus
Planetary
tx_v4
tx_bus
Battery
ess_v1
ess_bus
sum_ess
Electrical Accessory
accelec_v1
accelec_bus
Motor
mc_v1
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Differential
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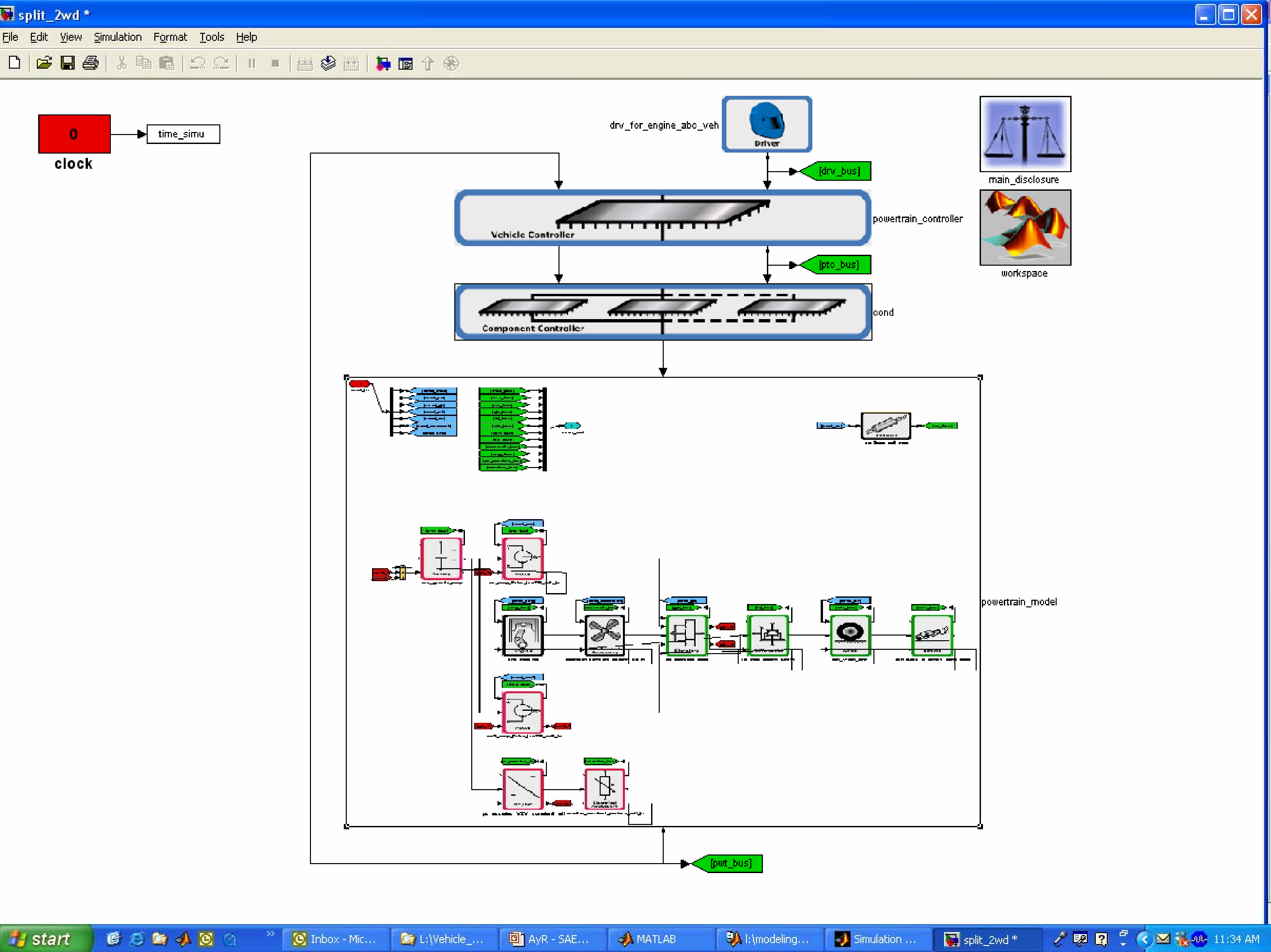
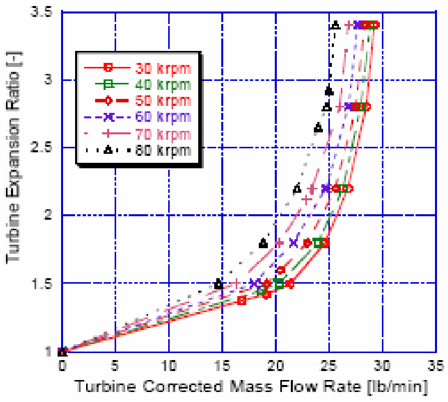
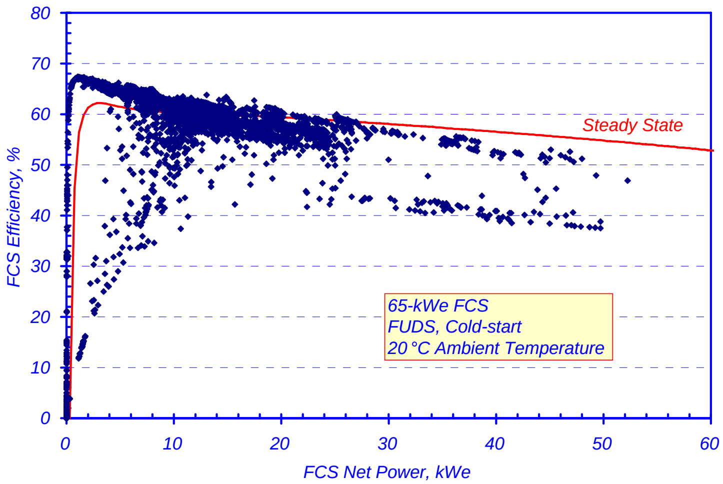
split_...
11:34 AM


split_2wd *
File Edit View Simulation Format Tools Help
0
clock
time_simu
drv_for_engine_abc_veh
Driver
[drv_bus]
main_disclosure
Vehicle Controller
powertrain_controller
workspace
[ptc_bus]
Component Controller
cond
powertrain_model
[pwt_bus]
start
Inbox - Mic...
L:\Vehicle_...
AyR - SAE...
MATLAB
I:\modeling...
Simulation ...
split_2wd *
11:34 AM

Different Models for Different Simulations

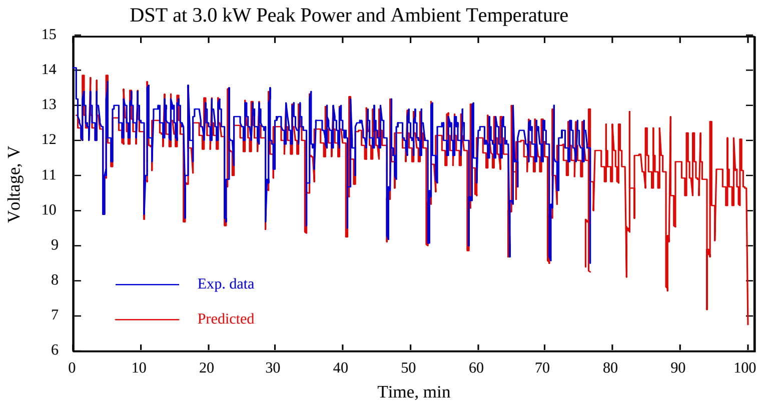
Transient, thermodynamic, physically-based, crank-angle resolved, turbocharged, intercooled <u>diesel engine.</u>





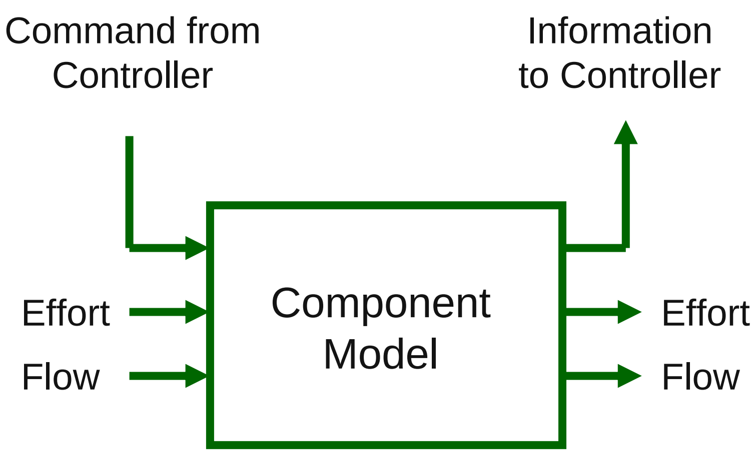
Transient, thermodynamic, physically-based, <u>fuel cell</u> models with Argonne, based on GCtool

The <u>battery</u> model developed at the Penn State GATE Center is a thermal-electrochemical coupled model constructed on computational fluid dynamics.



Model Complexity Selection Facilitated by Generic Component Model Format

- Models follow Bond Graph principle
- Consistent input/output nomenclature
- Plug-and-play component models
- Configuration easy to visualize in block diagram code



Mechanical Component
Effort = Torque
Flow = Speed

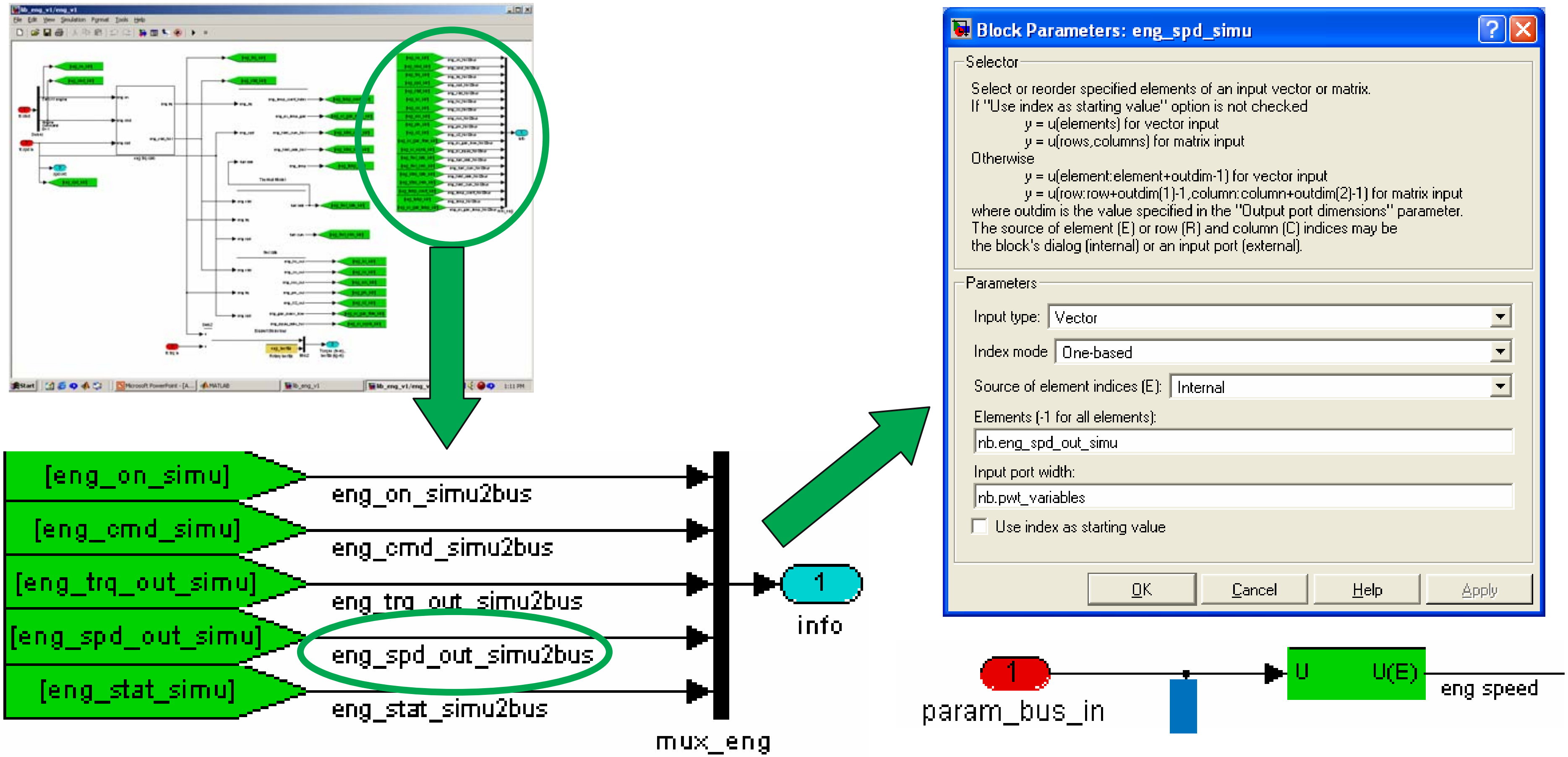
Electrical Component
Effort = Voltage
Flow = Current

Nomenclature Allows Intuitive Parameter Understanding

- Based on three parts:
  - Type of component (e.g.: eng = engine)
  - Type of data (e.g.: trq = torque)
  - Complement of information (e.g.: max = maximum)
- All the model parameters and variables are composed using these three parts

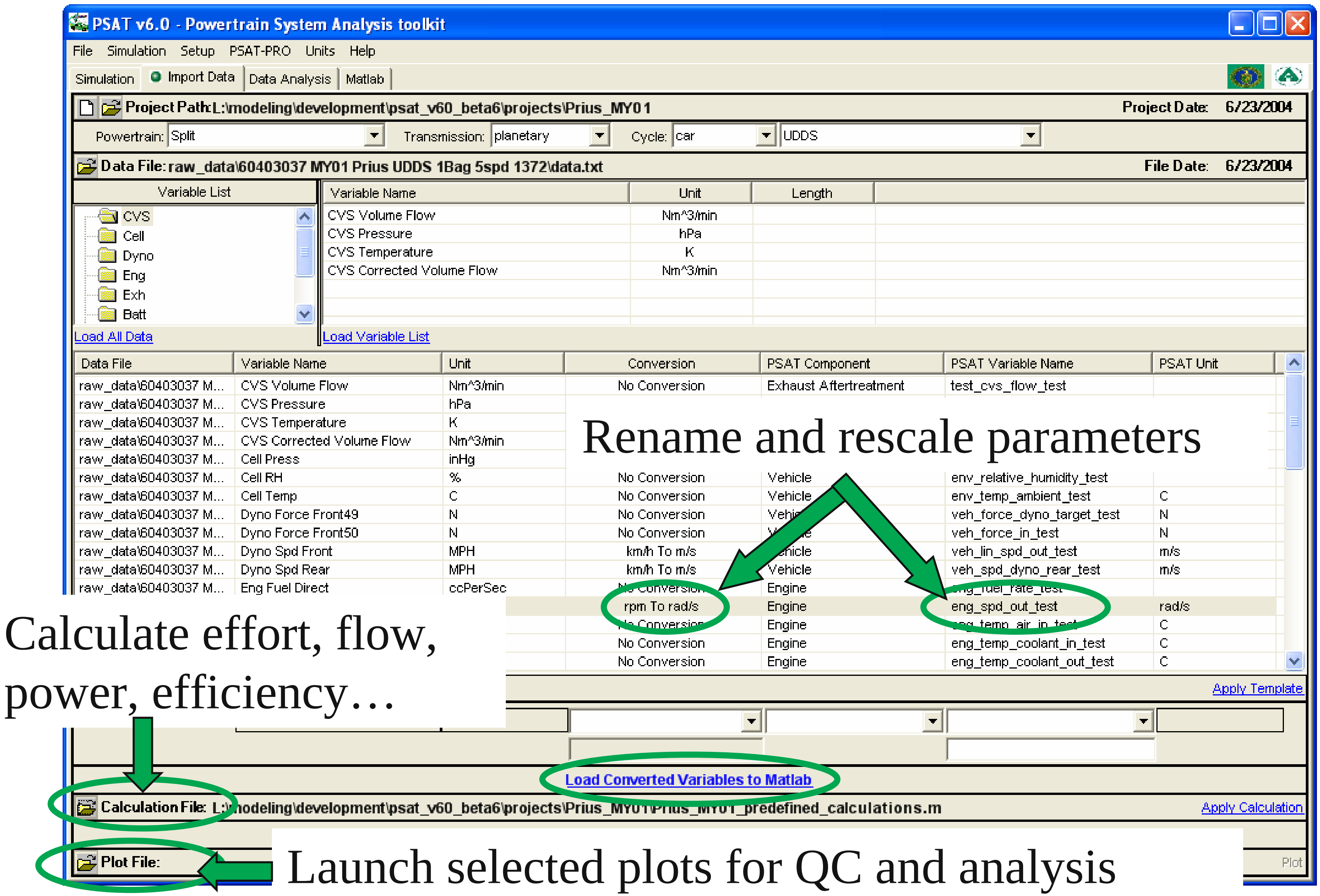
Parameter	Type of component	Type of data #1	Type of data #2
eng_spd_out_simu	"eng" for engine	"spd" for speed	“out” for output
mc_volt_in_simu	"mc" for motor controller	"volt" for voltage	“in” for input
ptc_eng_trq_max_simu	Engine information used in the controller ("ptc")	"trq" for torque	"max" for maximum

Information Bus Automatically Created



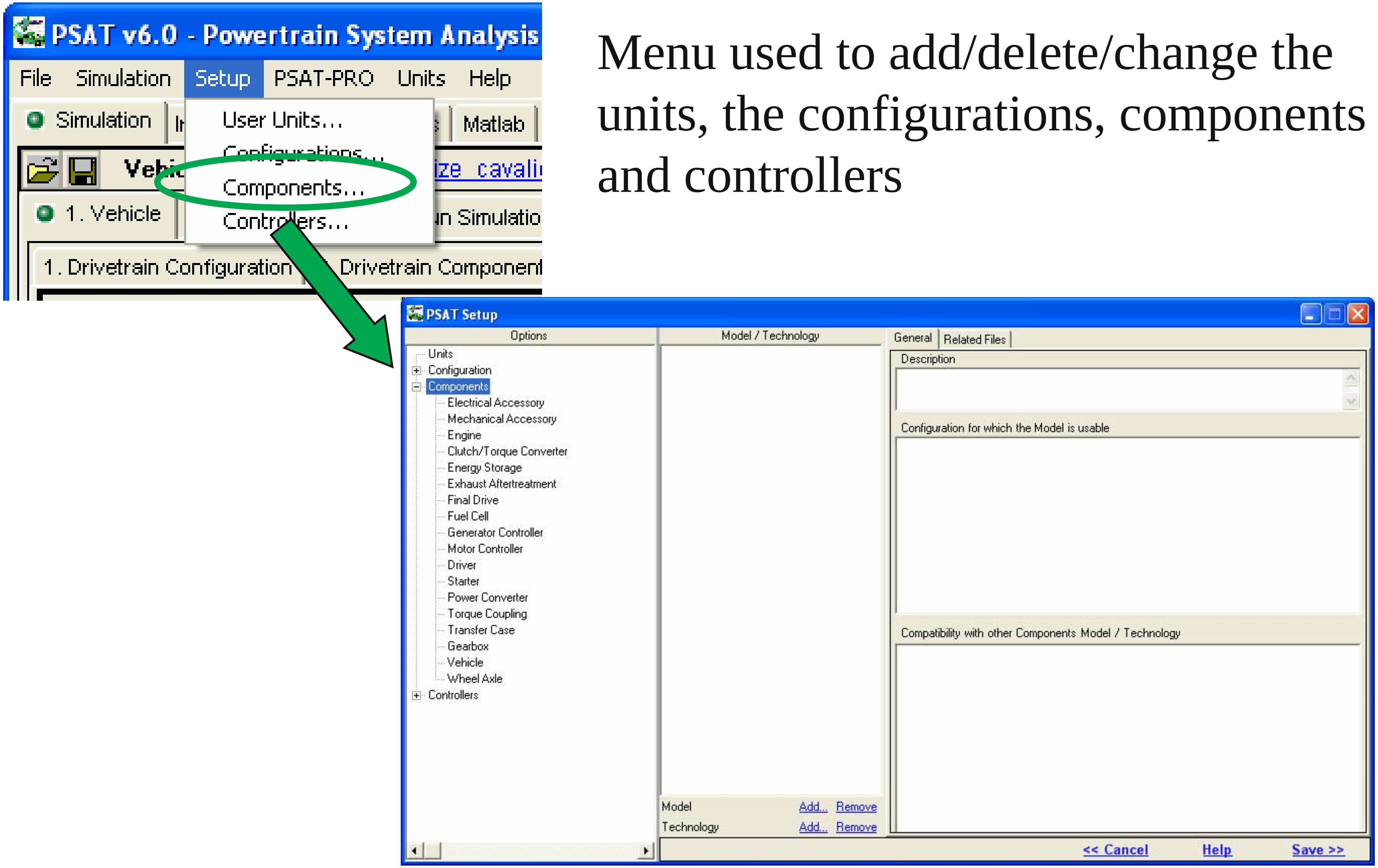
Name of the line => "name_parameter"2bus

Test Data Post-processing Facilitates Validation

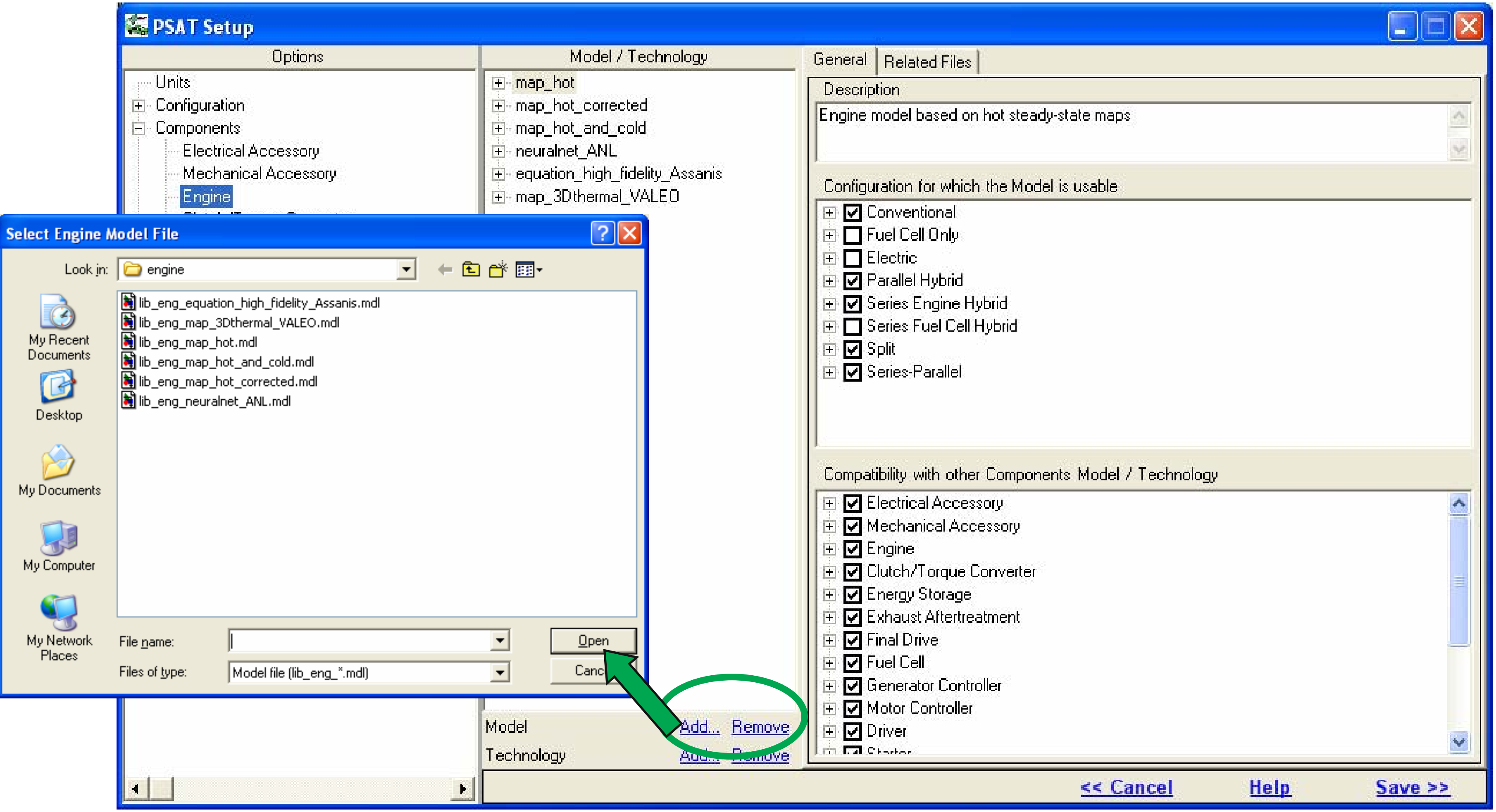


Proprietary Information Are Added Without Code Modification

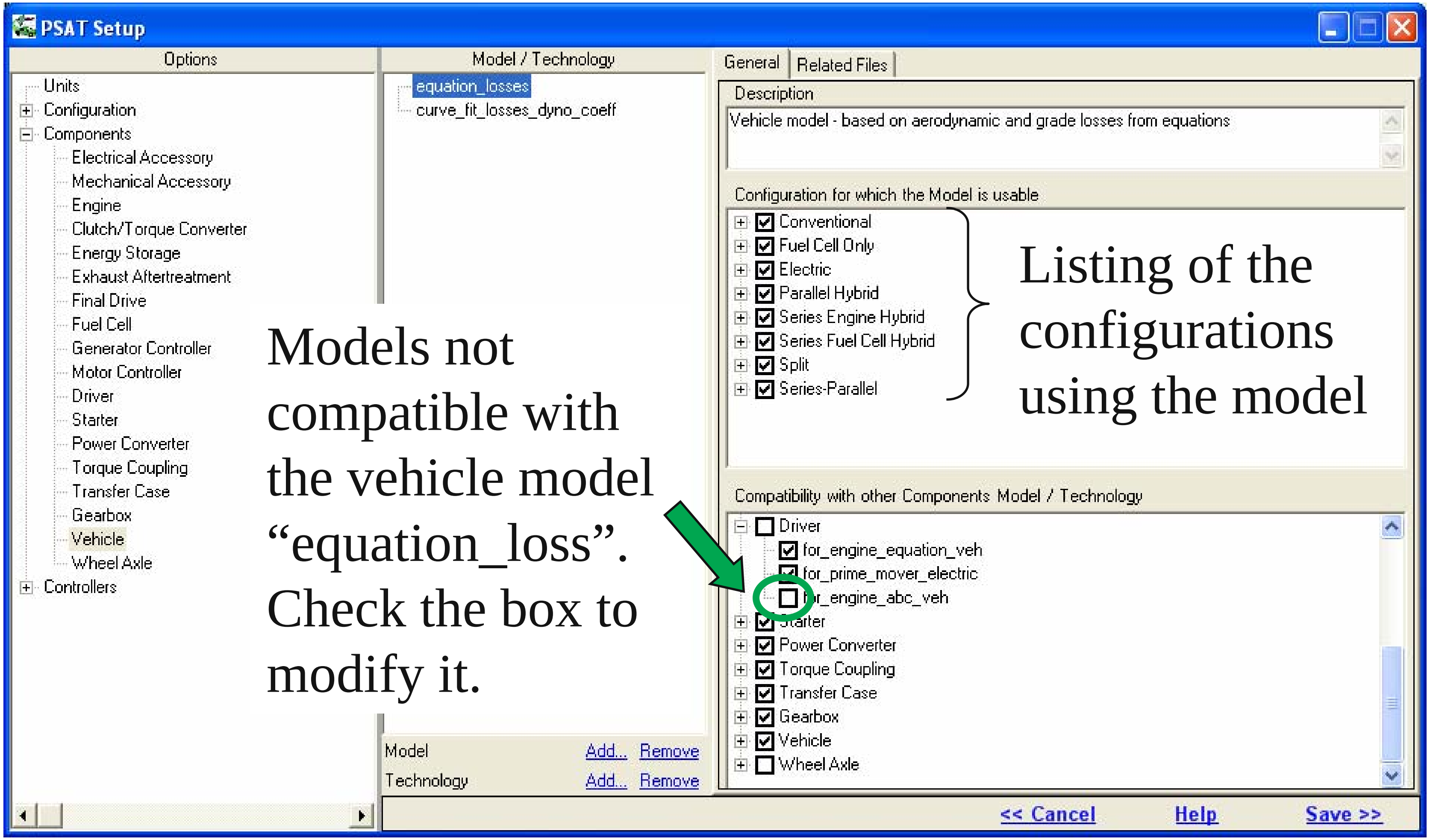
Menu used to add/delete/change the units, the configurations, components and controllers



Add/Remove Model



Compatibility Is Managed For the Users



Three Year CRADA with GM

- The goal is to develop a Plug-and-Play Powertrain and Vehicle Model Architecture and Development Environment to support the rapid evaluation of new powertrain/propulsion technologies for improving fuel economy and emissions through virtual design and analysis in a math-based simulation environment.
- Permit models to be developed by anyone and everyone (Universities, National Laboratories, Manufacturers, and Suppliers (big and small)) through a common language and means of exchanging technology.
- Easy exchange of models within and between companies.

Objectives for Engine and Aftertreatment Model Development

- **Engine models/maps**
  - **performance, fuel costs, emissions**
  - **conventional and advanced combustion modes (HCCI, PCCI, LTC etc.)**
  - **regular and emerging fuels (gasoline, diesel, hydrogen etc.)**
- **After treatment models**
  - **performance, costs (fuel penalty, aging etc.)**
  - **systems integration and control**
  - **failure modes**

Approach for Engine and Aftertreatment Model Development

- **Engine maps**
  - **conventional and high efficiency clean combustion (HECC/PCCI)**
  - **regular mode (lean or stoic) & special modes for facilitating regeneration of after treatment devices (e.g., rich operation for LNT regeneration, high temperature lean operation for DPF regeneration)**
  - **source : experiments or simulations (numerical experiments)**
- **Define strategies/schemes for linking devices with engine maps during nominal & NOx/SOx/PM regeneration**
- **Deliverables: PSAT sub-models for advanced combustion engines & emissions controls, enabling assessment of vehicle fuel economy & emissions impact**

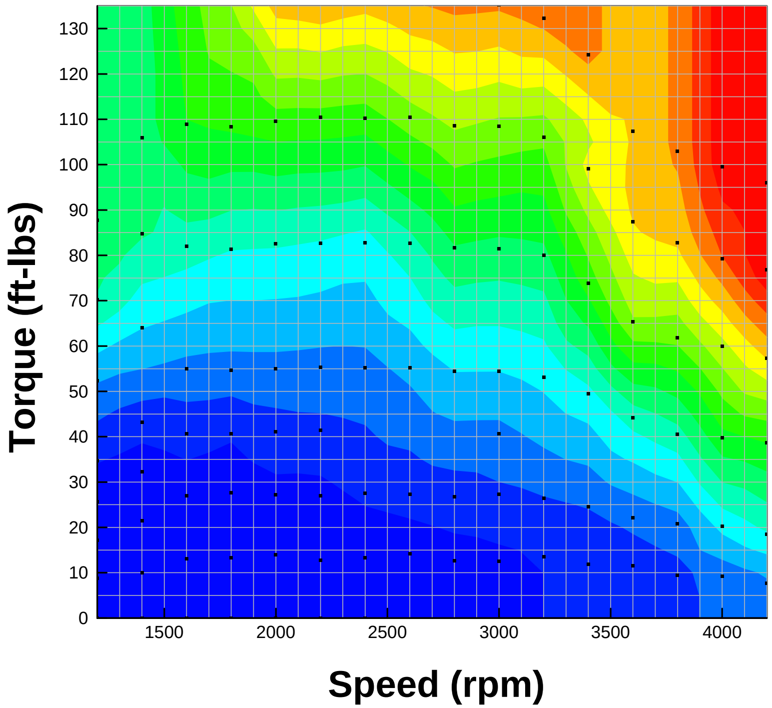
Recent Engine & Aftertreatment Modeling Accomplishments

- **Defined approach for expanding Mercedes engine map to include LNT regeneration states**
- **Simulink Chalmers LNT model operating and fitted with CLEERS protocol data for a Umicore catalyst**
- **Initial Simulink LNT and engine supervisor modules constructed and now undergoing tests in PSAT**
- **0-D DPF MatLab model written and undergoing testing prior to Simulink implementation**

Standard Engine Mapping Approach for PSAT Relies on Experimental Data Tabulation

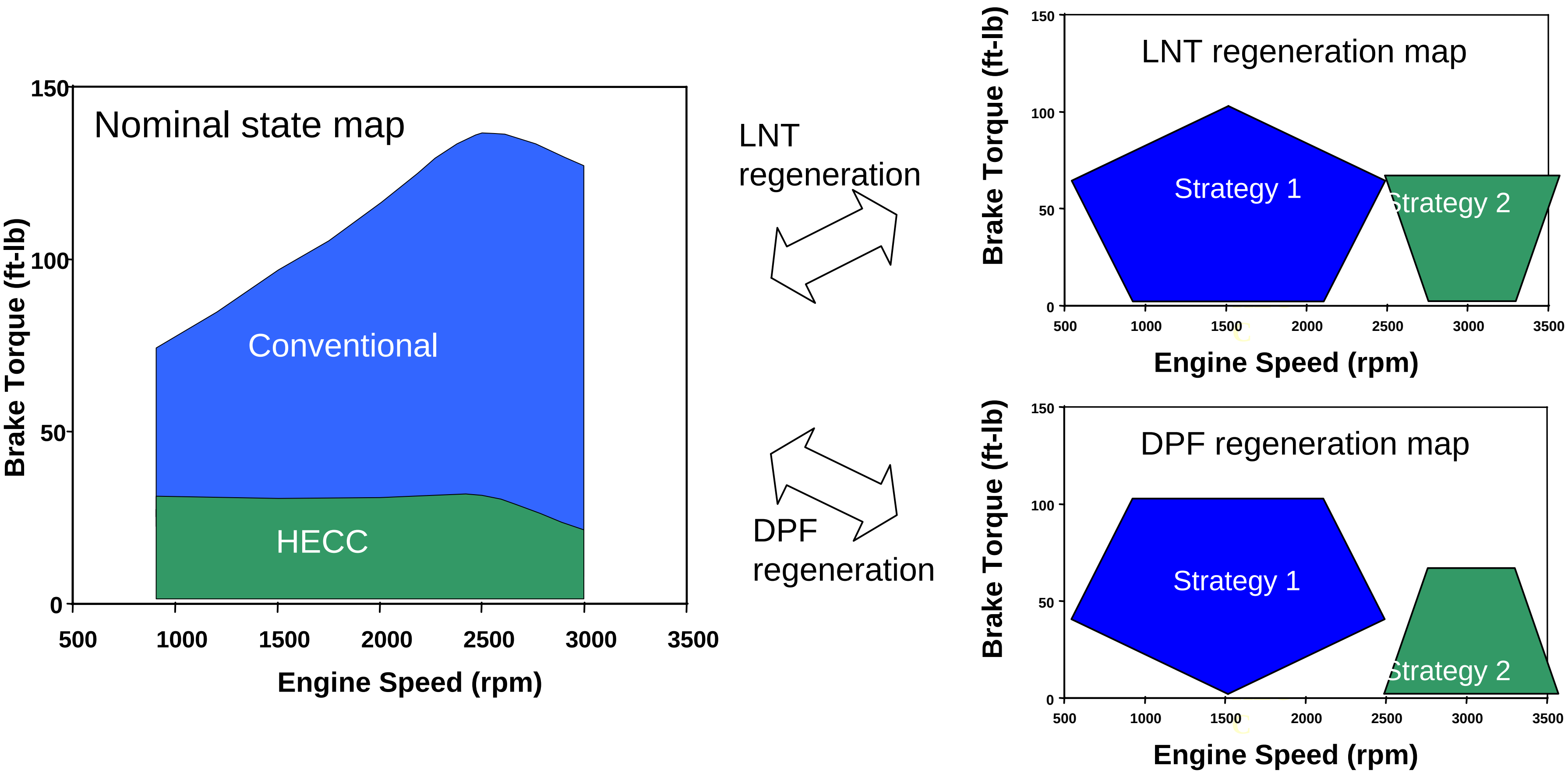
- **Detailed speed-load sweep provides data to map engine (e.g., 109 operating conditions for MB 1.7-L)**
- **Data includes fuel consumption, intake temperature, intake pressure, exhaust temperature, exhaust mass flow rate, and regulated pollutants**
- **Square matrix generated by nearest-neighbor interpolation based on measured data**

Example NO_x Map



UT-BATTELLE

Our plan is to Create Parallel Engine Maps for LNT and DPF Regeneration States



- **Regeneration maps derived from limited data, WAVE simulations**
- **Engine switching triggered by LNT/DPF state indicators, engine supervisor assessment**

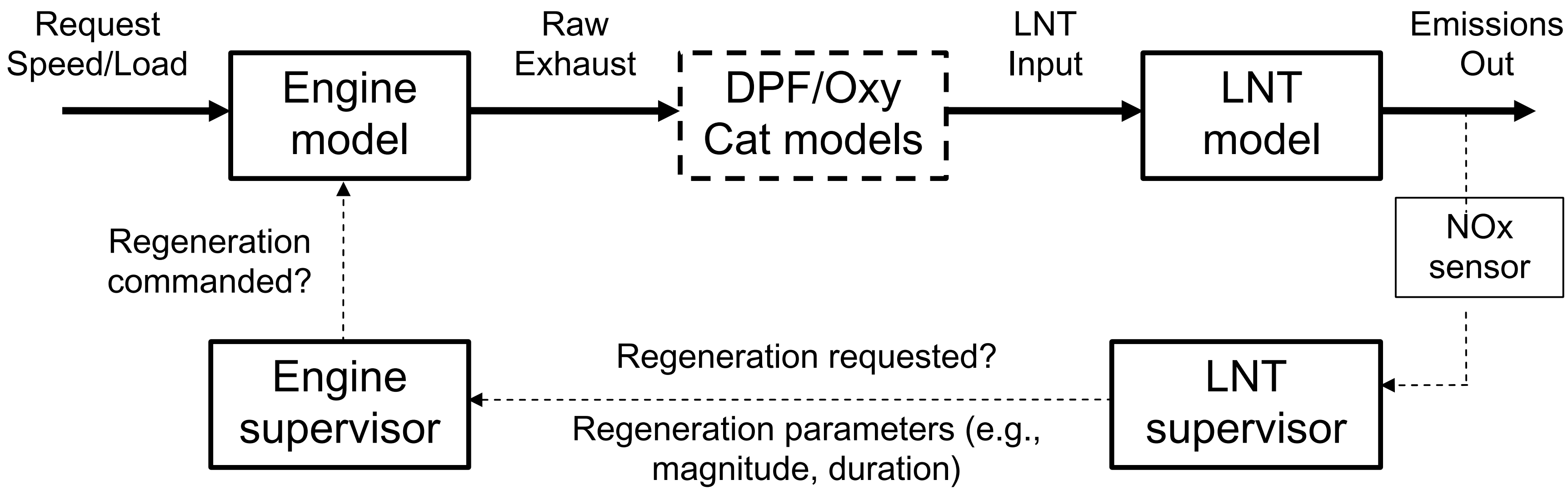
LNT Simulink Model (Ind. Eng. Chem. Res. 2005, 44, 3021)

- **Based on a Chalmers/GM model (Ind. Eng. Chem. Res. 2005, 44, 3021)**
- **Accounts for:**
  - **NOx capture in nitrite/nitrate form and C_3H_6 based regeneration**
  - **NO<=>NO_2 inter-conversion**
  - **Diffusion resistance to bulk nitrite/nitrate storage (shrinking core)**
- **Extensions**
  - **CO/H_2 based regeneration (as in CLEERS protocol)**
  - **CO equivalent to H2 in terms of reducing capacity**
  - **Oxygen storage**
  - **calibrated using CLEERS protocol data for a Umicore catalyst**
  - **S poisoning (not available yet)**
  - **De-sulfation (not yet available)**

Regeneration schemes

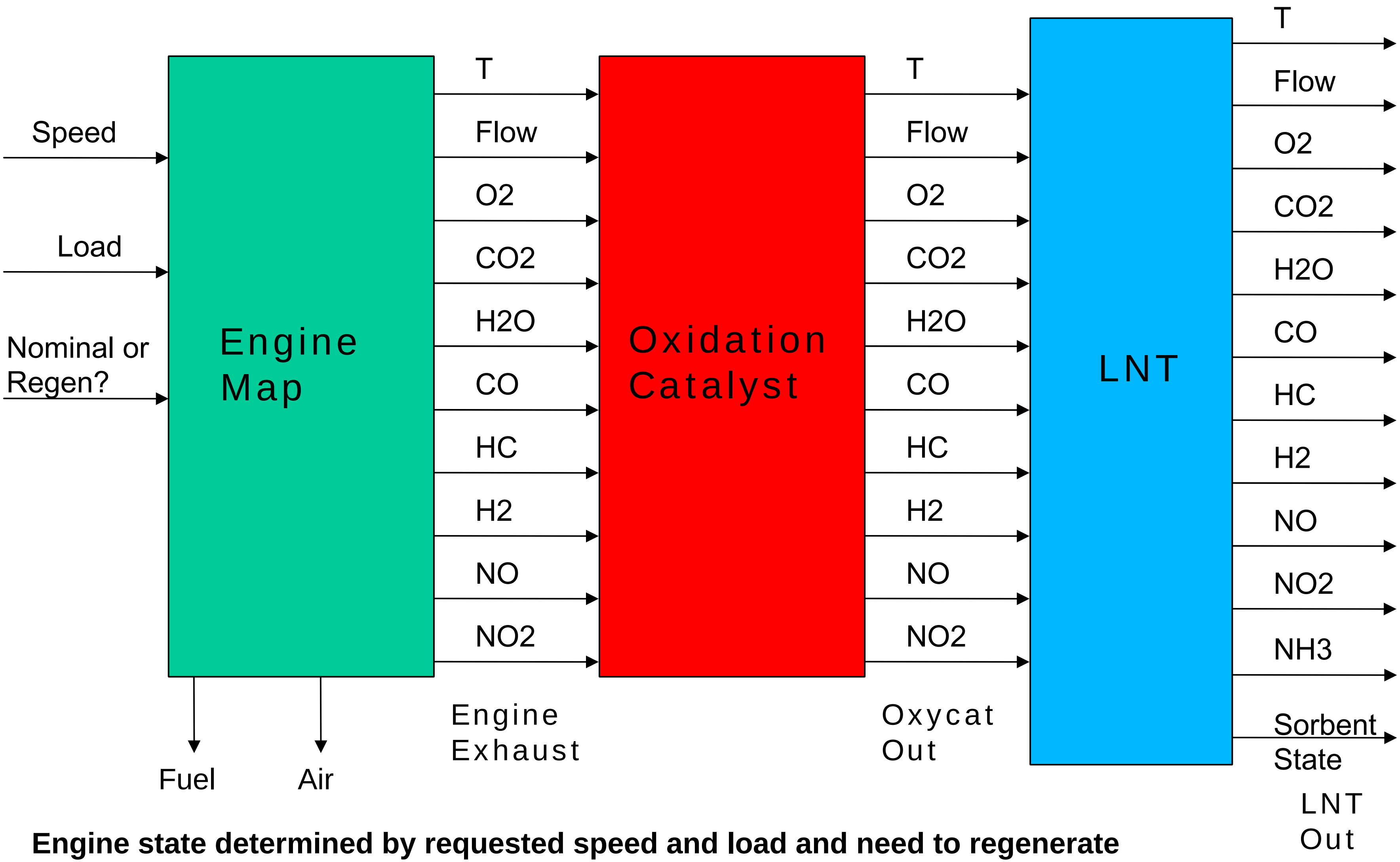
- **No regeneration when LNT-out T < 150ºC**
- **Minimum period of lean operation between regenerations**
- **Downstream NOx sensor based engine control**
  - **regenerate if LNT-out NOx conc exceeds a user-specified level**
  - **fixed regeneration interval (user-specified)**
  - **impractical (NOx sensors are expensive, hard to measure NOx at low concentrations)**
- **Downstream UEGO sensor based engine control**
  - **regenerate at fixed intervals**
  - **stop regen when A/F drops below a specified value (e.g., 14.1)**
- **Engine map based control : no feedback**
  - **Integrating NOx influx into the LNT**
  - **start a regeneration when the integrated NOx exceeds a given fraction (say 25%) of the storage capacity**

LNT-out NOx feedback based regen : optimal performance



- **LNT supervisor monitors LNT state and requests regeneration when needed**
- **Engine supervisor commands regeneration when speed/load/other constraints permit**
- **Regeneration command switches engine to LNT regeneration map for specified period**
- **Engine supervisor must also prioritize LNT regeneration relative to DPF regeneration and other emission control requests**

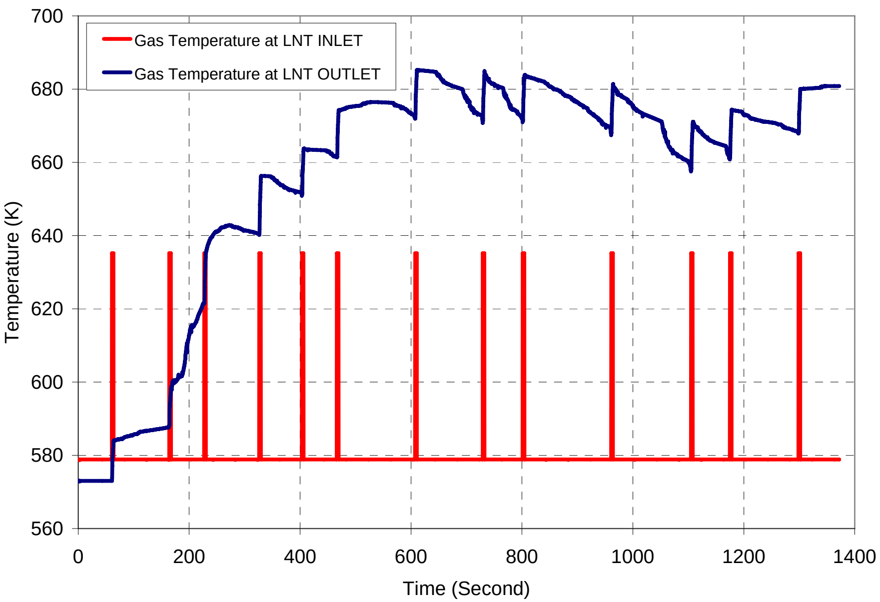
Integration of various sub-models with in PSAT

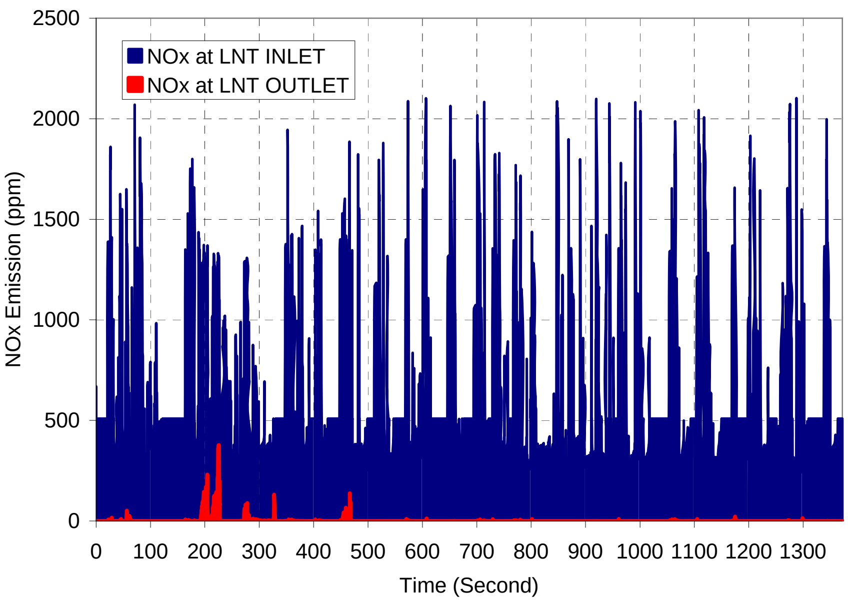


Engine state determined by requested speed and load and need to regenerate

Predicted LNT performance during a (UDDS) cycle on a Mercedes 1.7-liter engine with an initially warm catalyst*

Regen strategy : NOx sensor feedback based engine control





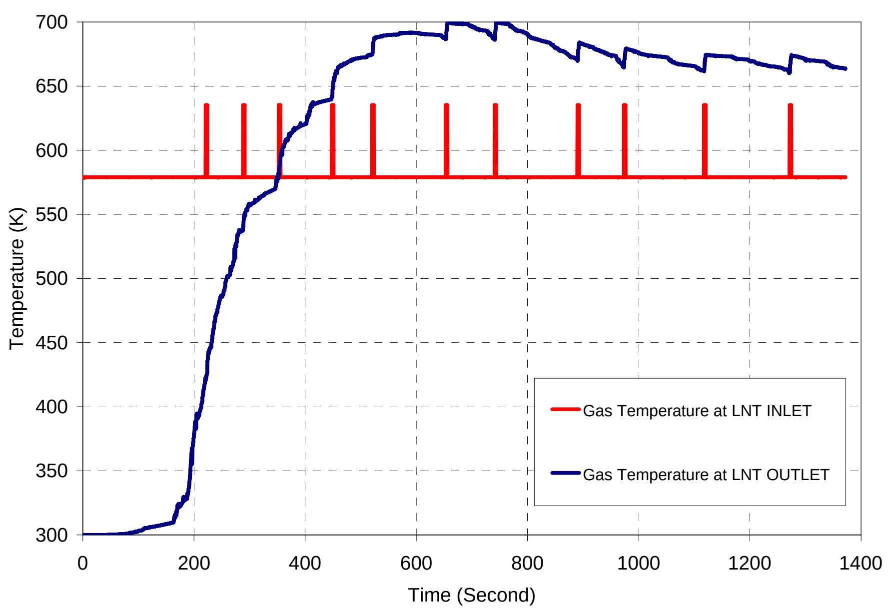
Overall NOx reduction efficiency : 98.6%

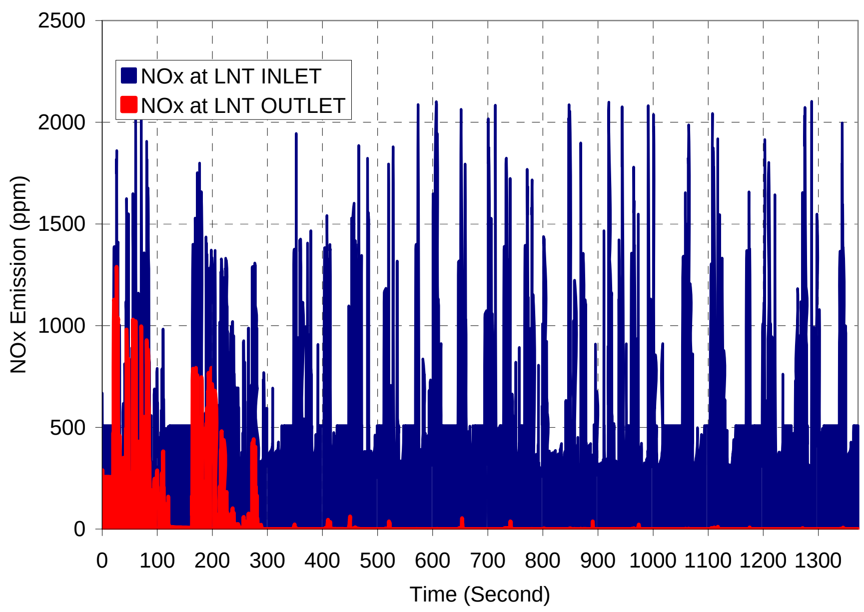
Fuel penalty due in operating and regenerating the LNT : 3.0% (estimate based on a single regeneration conditions, full regeneration map not available)

***Initial catalyst T : 300°C, Initial LNT-in gas temperature : 310°C**

Predicted LNT performance during a (UDDS) cycle on a Mercedes 1.7-liter engine with an initially cold catalyst*

Regen strategy : NOx sensor feedback based engine control



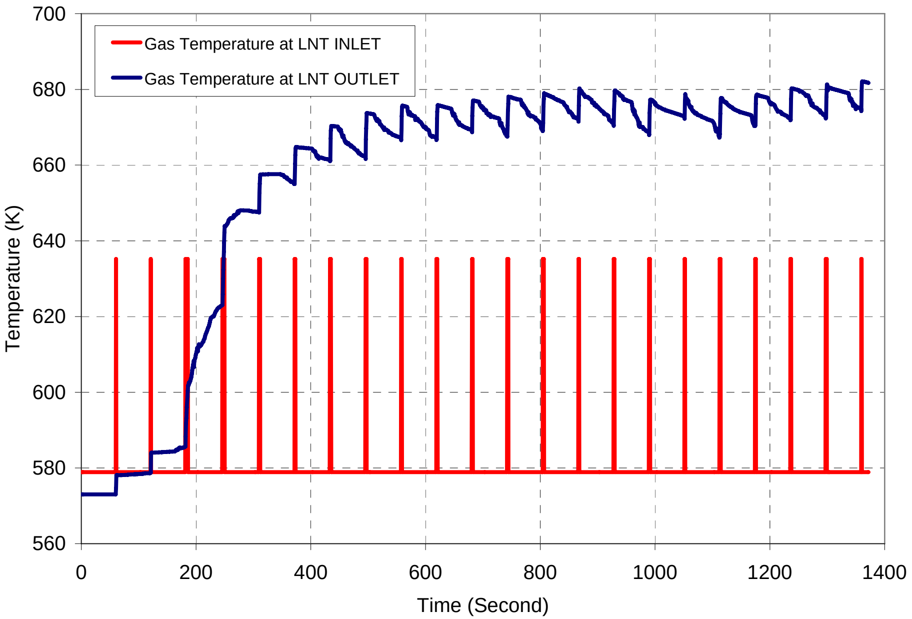


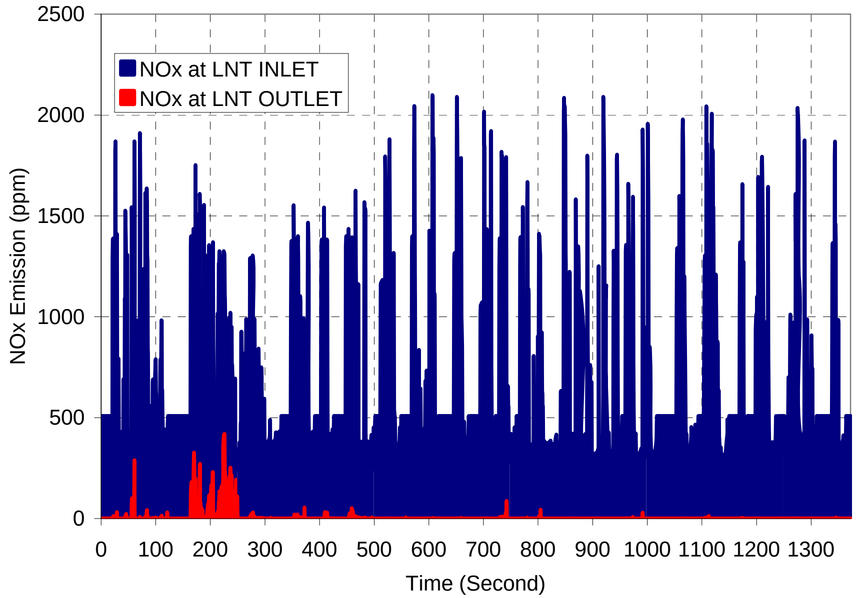
Overall NOx reduction efficiency : 88.50%
Fuel penalty due in operating and regenerating the LNT : 2.04% (estimate based on a single regeneration conditions, full regeneration map not yet available)

***Initial catalyst T : 27ºC, Initial LNT-in gas temperature : 310ºC**

Predicted LNT performance during a (UDDS) cycle on a Mercedes 1.7-liter engine with an initially an initially warm catalyst*

Regen strategy : UEGO sensor feedback based engine control





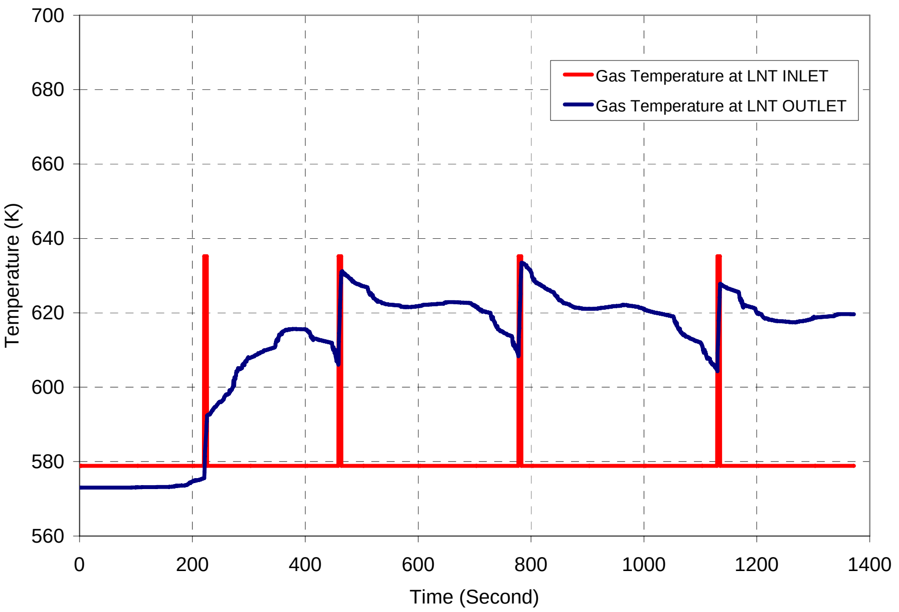
Overall NOx reduction efficiency : 97.7%

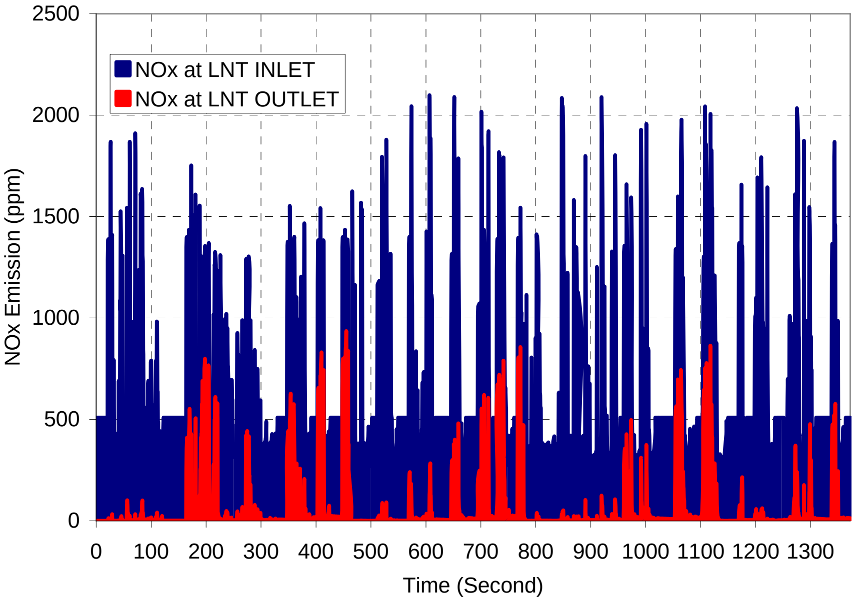
Fuel penalty due in operating and regenerating the LNT : 6.18% (estimate based on a single regeneration conditions, full regeneration map yet not available)

***Initial catalyst T : 300ºC, Initial LNT-in gas temperature : 310ºC**

Predicted LNT performance during a (UDDS) cycle on a Mercedes 1.7-liter engine with an initially warm catalyst*

Regen strategy : Engine map based control



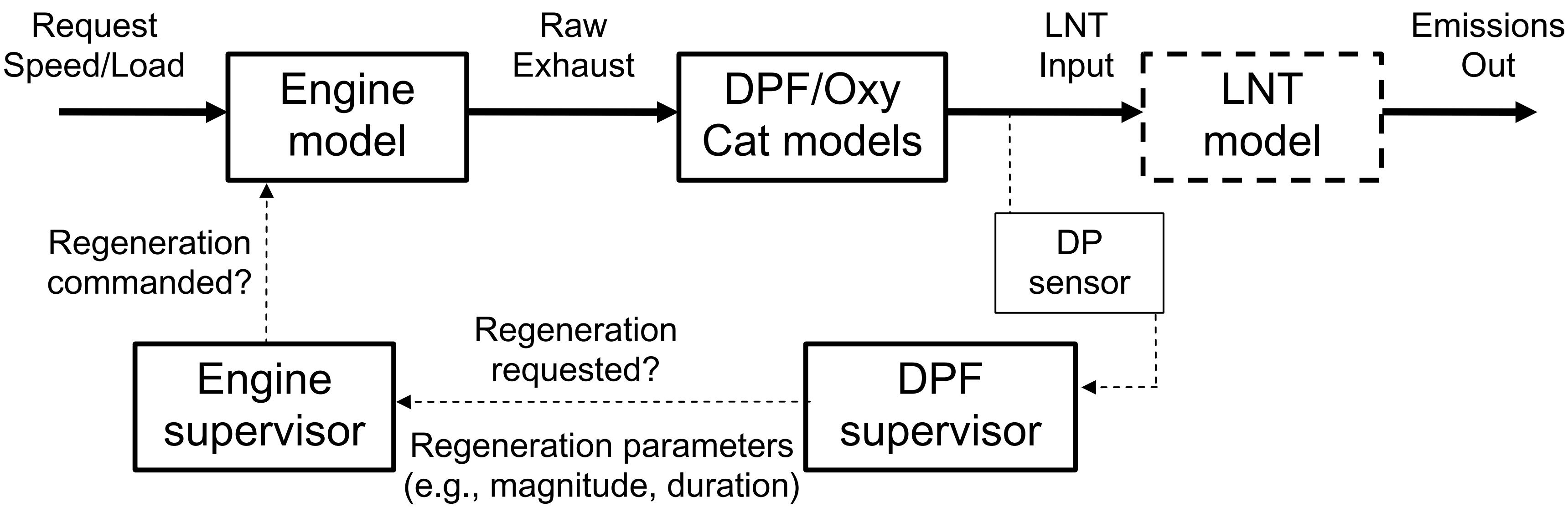


Overall NOx reduction efficiency : 81.0%

Fuel penalty due in operating and regenerating the LNT : 1.34% (estimate based on a single regeneration conditions, full regeneration map not available)

***Initial catalyst T : 300°C, Initial LNT-in gas temperature : 310°C**

Planned DPF regeneration logic



- **DPF supervisor monitors DPF state (pressure drop) and requests regeneration when needed**
- **Engine supervisor commands regeneration when speed/load constraints permit**
- **Regeneration command switches engine to DPF regeneration map for specified period**
- **Engine supervisor must also prioritize DPF regeneration relative to LNT regeneration and other emission control requests**

Future Plans (1)

- **Update and supplement LNT and DPF sub-models**
  - **Other regeneration schemes (suggestion welcome)**
  - **Aging/S effects**
  - **test various after treatment configurations (i.e., integration of various sub-models in series)**
- **Expand engine maps**
  - **LNT/DPF regeneration states=> full FTP capability**
  - **1.9-L GM with conventional and advanced combustion modes**
  - **Honda Accord with cylinder deactivation**
  - **Alternative and conventional fuels (e.g., ethanol, biodiesel)**
- **Evaluate new engine and aftertreatment technologies with respect to FreedomCAR efficiency and emissions targets**
  - **Phase 1: Use Multi-mode LTC MB engine map (current platform)**
  - **Phase 2: Use GM engine map (future platform)**

Future Plans (2)

- **Add SCR device sub-model**
- **Other baseline regeneration strategies for both LNT and DPF for inclusion in PSAT (input from CLEERS community very important)**

Contact information

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