Residual Gas Fraction Estimation in Gasoline Engines

(GT-Power vs. Semi-empirical Model)

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Background

- Residual Gas Fraction (RGF) has a significant influence on flame propagation, combustion stability, misfire, and knock
  - influencing emissions (NOx, HC), power and fuel economy
- Industry Examples Include
  - Turbocharged engines with cooled EGR and $\lambda=1$ – Knock mitigation
  - Variable Valve Events (VVE) strategies to augment fuel economy via RGF control

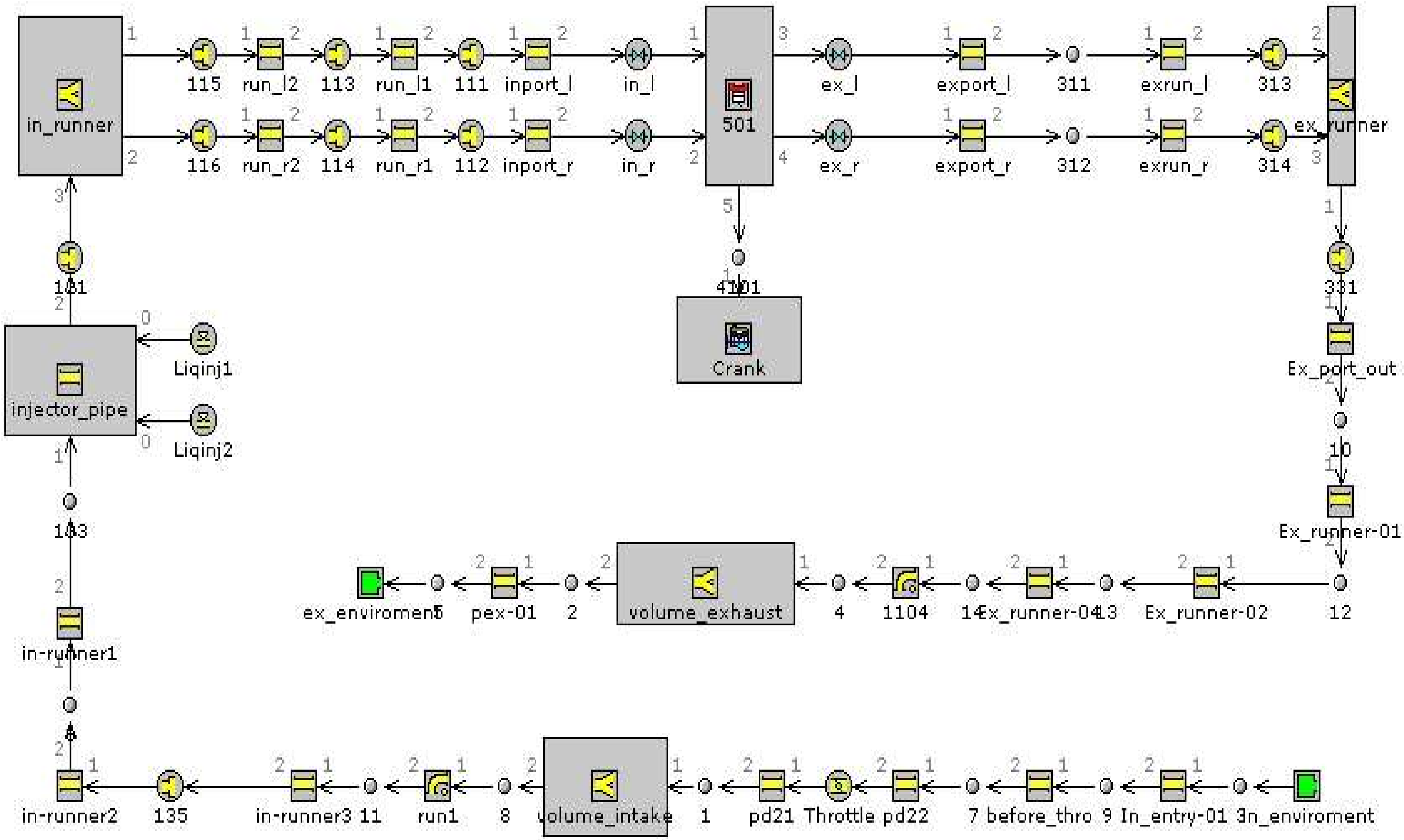
Motivation

- Quantifying in-cylinder gas composition is essential to the development and calibration of SI engines
- Experimental techniques to infer RGF (CO_2, NO, HC, H_2O)
  - Expensive and intrusive
  - Limitations (sampling rate, sensor location, etc.)
- Numerical techniques

Numerical Techniques

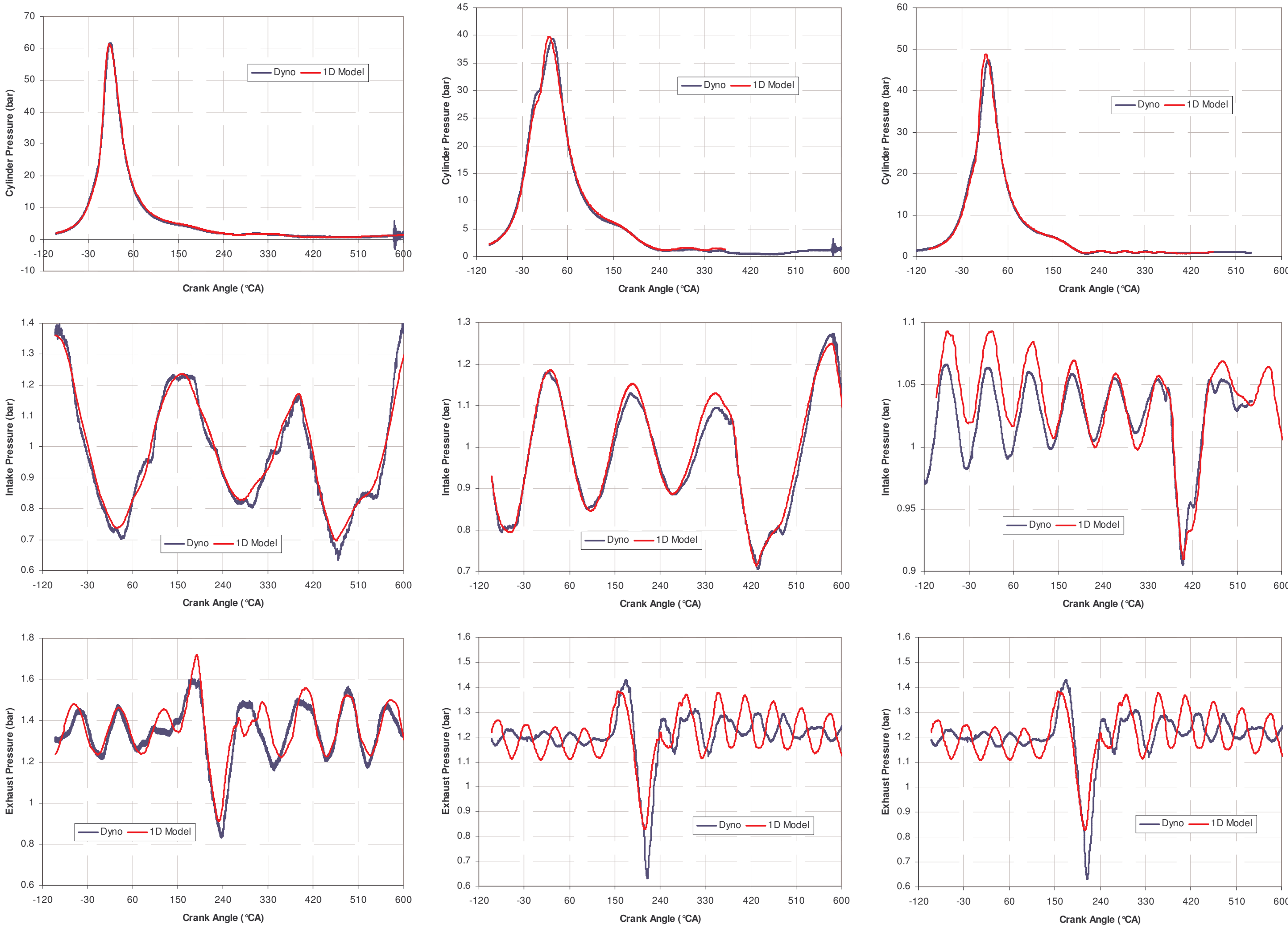
Empirical Formulae		0D Gas Exchange Model		1D Gas Exchange Model	
Overlap Factor (OF) Model	**Semi-empirical (e.g. Shayler's)**	**Conditional Gas Exchange**	**Gas Exchange**	**Gas Exchange**	**Detailed Simulation**
Engine specific		**Engine configuration based[2]**			
I/P: intake pressure and temperature, exhaust pressure, A/F ratio, CR, etc… ECL and external EGR are not considered	I/P: intake pressure and temperature, exhaust pressure, A/F ratio, CR, volumetric efficiency and external EGR One constant fits all RPM and ECL are not considered	I/P: intake pressure and temperature, exhaust pressure, and engine configuration $P_{av\text{-}int} < P_{Cyl} < P_{av\text{-}exh}$ $P_{av\text{-}int} = P_{Cyl} = P_{av\text{-}exh}$ $P_{av\text{-}int} > P_{Cyl} > P_{av\text{-}exh}$ Dependent of pressure transducer location	I/P: intake pressure (dynamic), intake temperature, exhaust pressure (dynamic), cylinder pressure and engine configuration Dependent on pressure transducer location	I/P: intake pressure (dynamic), intake temperature, exhaust pressure (dynamic), engine running condition and engine configuration Calibrated 1D simulation model (gas exchange only) Independent of pressure transducer location	I/P: intake pressure and temperature, exhaust pressure, engine running condition and engine configuration Calibrated 1D simulation model Independent of pressure transducer location
On-line, off-line and Real Time[1]			**On-line and off-line**		

1D GT-Power Model



Model Validation w/ Head "A" (1/2)

6000 RPM WOT | **4000 RPM WOT** | **2000 RPM WOT**

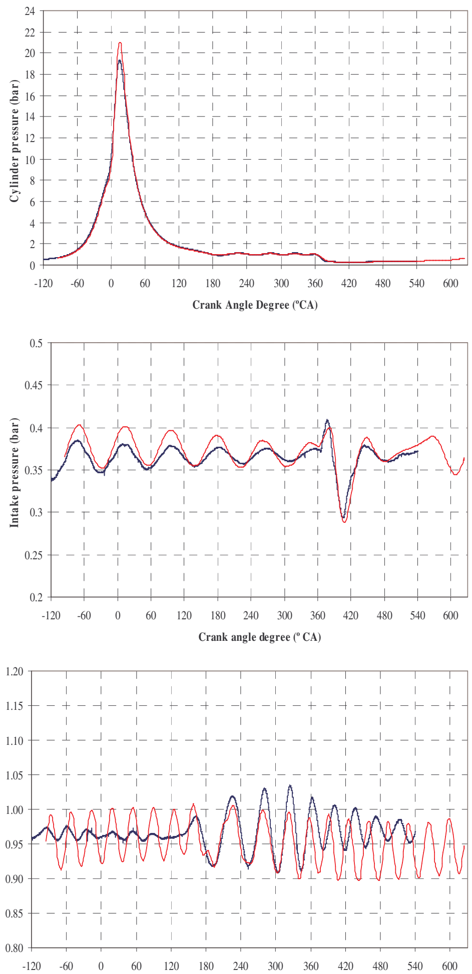


1D Model

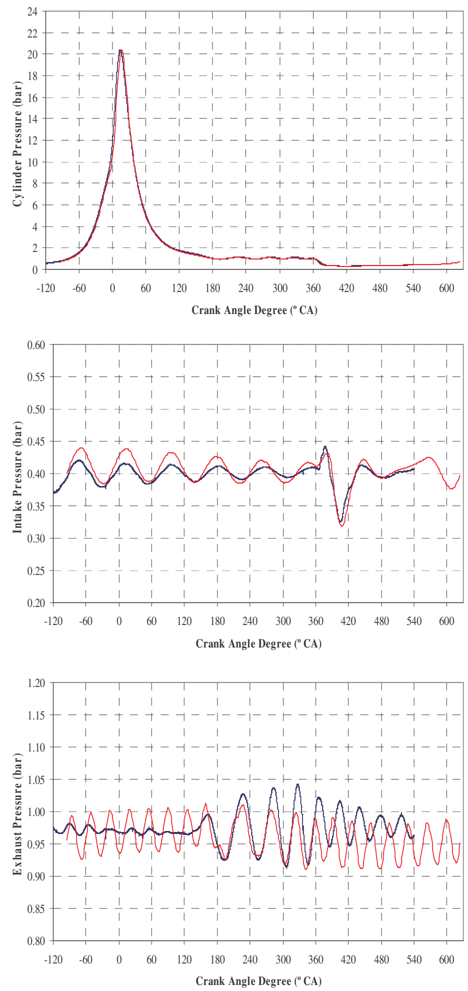
Dyno

Model Validation w/ Head "A" (2/2)

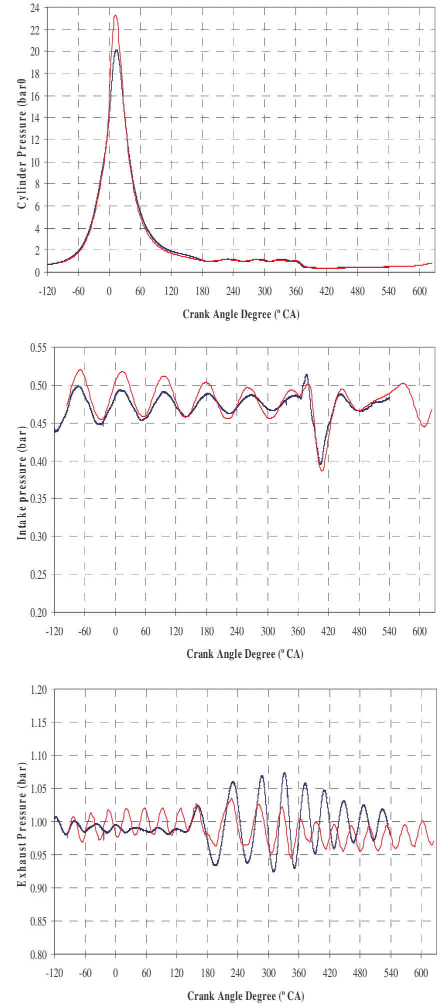
λ=1.036 at 2000 rpm w/ PB



λ=1.223 at 2000 rpm w/ PB



λ=1.58 at 2000 rpm w/ PB



1D Model

Dyno

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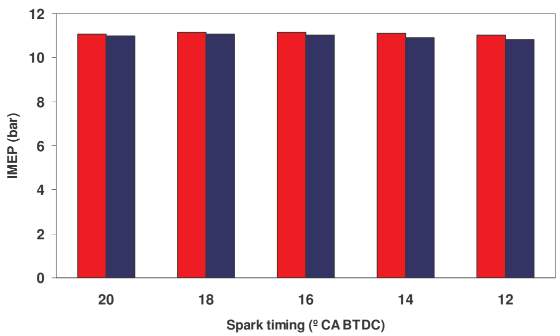
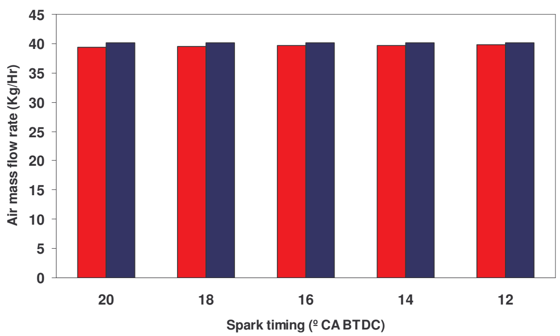
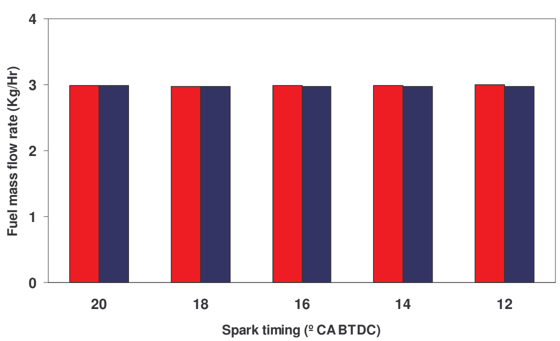
Performance Prediction (Head "B")

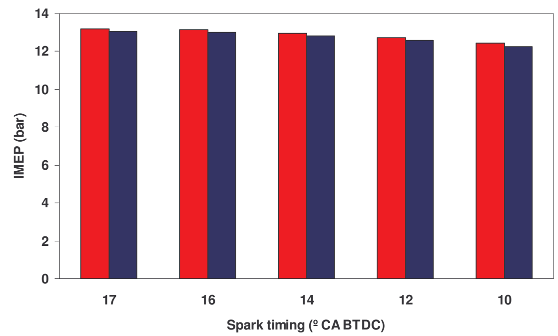
2000 RPM WOT

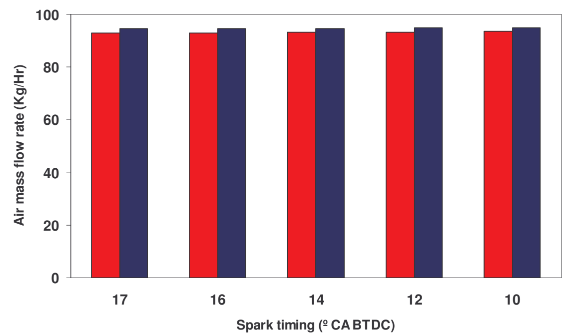


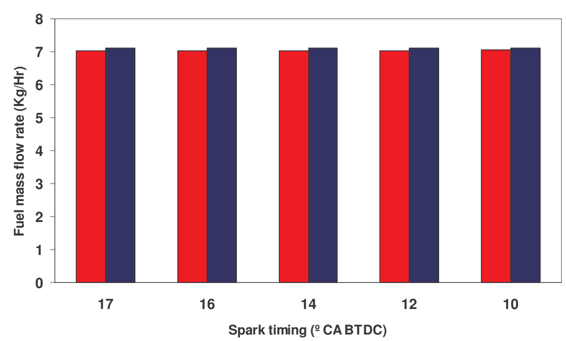




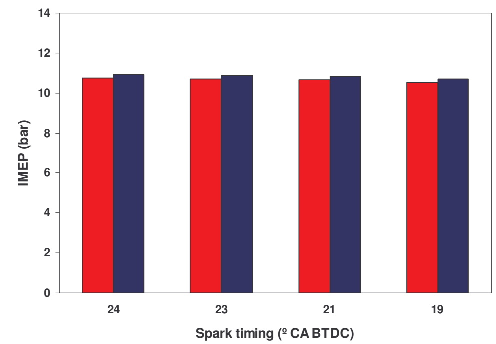
4000 RPM WOT

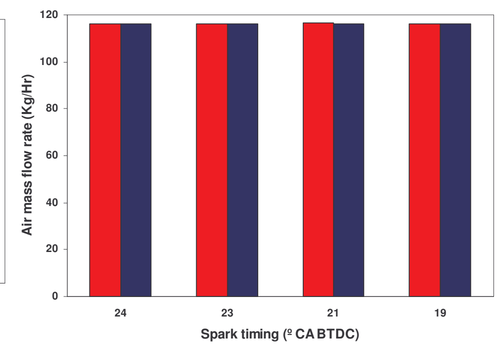


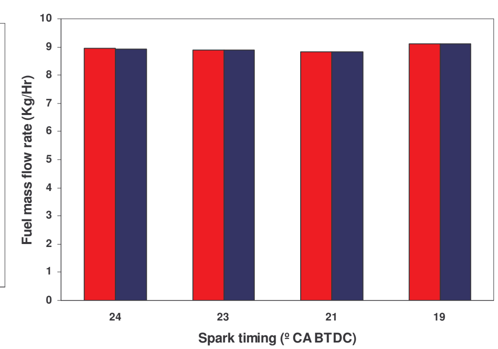




6000 RPM WOT







1D Model

Dyno

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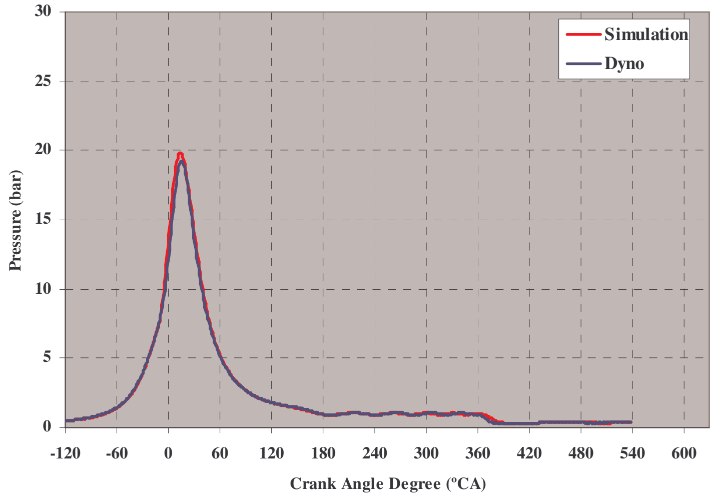
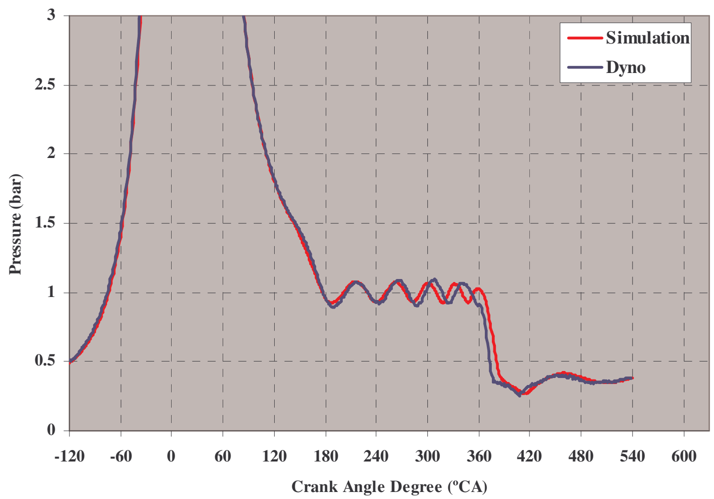
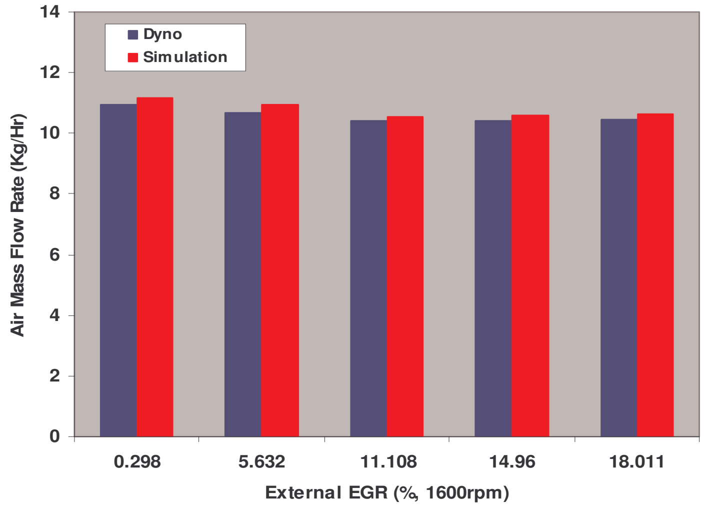
Performance Prediction (Head “B”)

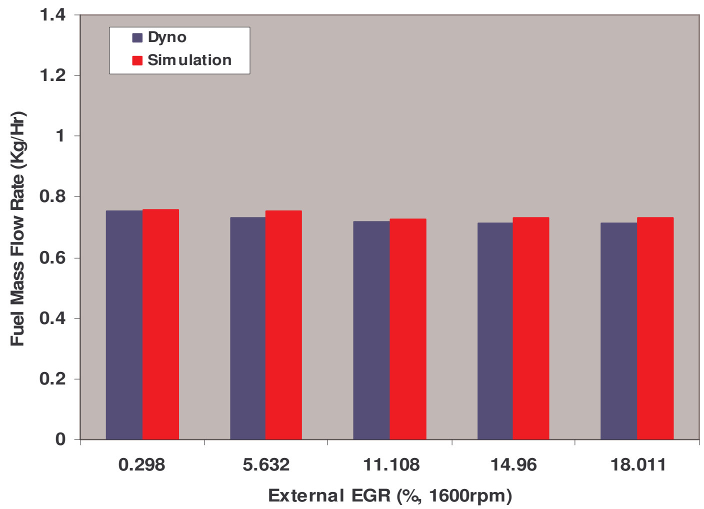
1600 RPM PT w/ 0% EGR





1600 RPM PT, external EGR sweeps

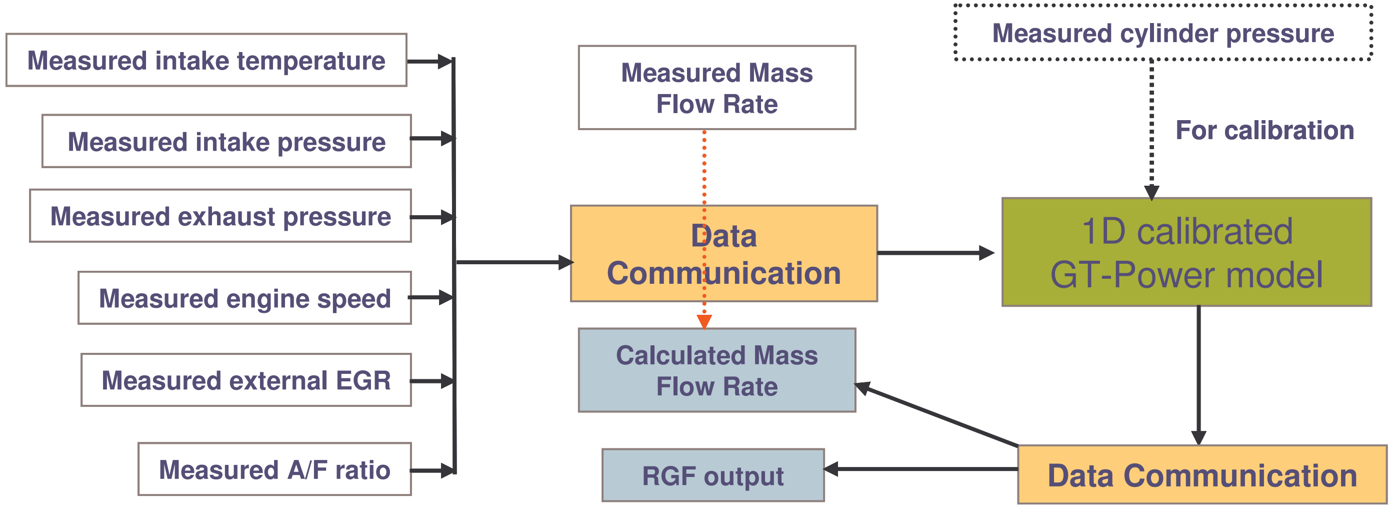




1D Model

Dyno

1D GT-Power Model

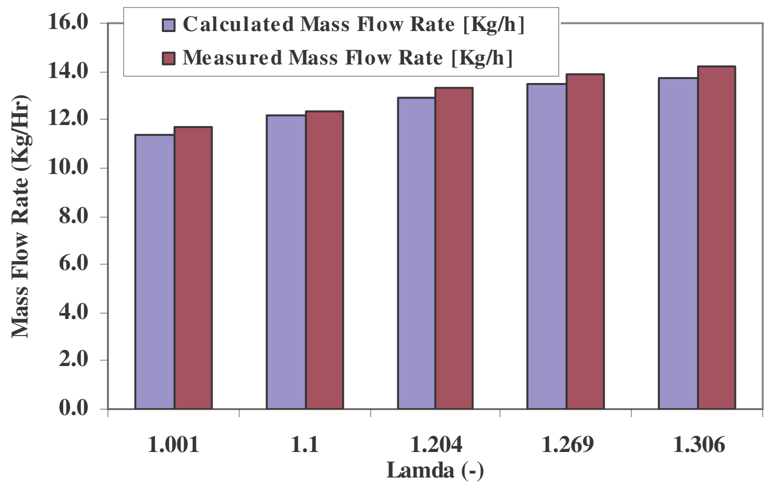


Residual Gas Fraction Calculation with GT-Power Model

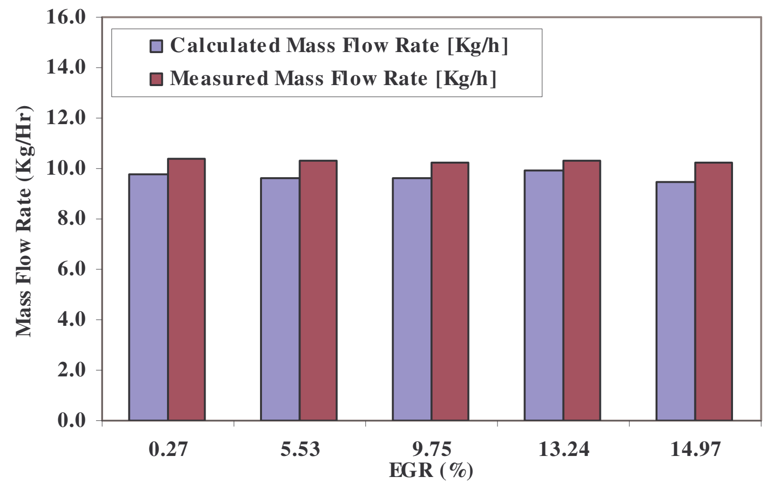
Test No.	GT-Power Model	Pressure File	Engine Speed	Fuel/Air Ratio	External EGR	Intake Temperature	Measured Mass Flow Rate	RGF	In-Cylinder Gas Fraction	Calculated Mass Flow Rate
			[RPM]	[-]	[%]	[K]	[Kg/h]	[%]	[%]	[Kg/h]
1	gt00101	ASE_042_1	2001.1	0.0830	4.03	309.15	12.13	15.40	18.19	11.21
2	gt00101	ASE_042_2	1999.8	0.0740	5.09	308.85	12.81	14.54	18.10	11.92
3	gt00101	ASE_042_3	1999.9	0.0660	5.96	308.55	13.74	13.85	18.06	12.59
4	gt00101	ASE_042_4	2000.6	0.0610	8.23	308.35	14.30	13.09	18.89	13.14
5	gt00101	ASE_042_5	2000.5	0.0590	11.57	308.25	14.64	12.89	20.87	13.33
6	gt00101	ASE_043_1	1600.1	0.0840	0.27	307.95	10.88	15.84	16.03	9.55
7	gt00101	ASE_043_2	1600	0.0840	5.53	308.15	10.86	15.33	19.12	9.95
8	gt00101	ASE_043_3	1599.7	0.0840	9.75	308.35	10.73	14.77	21.31	10.35
9	gt00101	ASE_043_4	1599.5	0.0840	13.24	307.55	10.74	14.00	22.79	11.11
10	gt00101	ASE_043_5	1600.2	0.0850	14.97	307.35	10.77	14.27	24.03	10.82

Further Validation

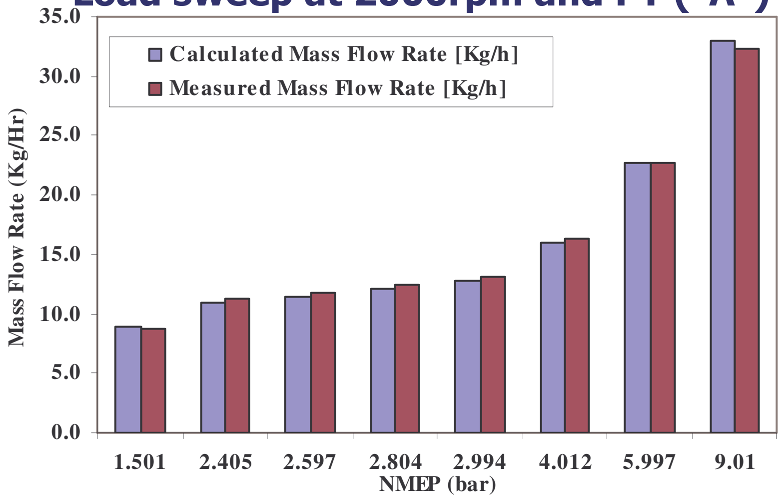
λ sweep at 2000rpm and PT (“A”)



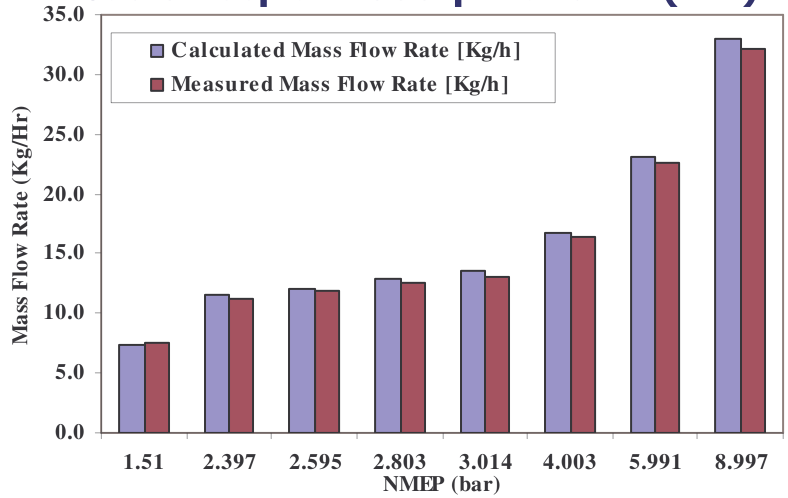
EGR sweep at 1600rpm and PT (“A”)



Load sweep at 2000rpm and PT (“A”)



Load sweep at 2000rpm and PT (“B”)



Objective

- To develop a simple, yet predictive model for RGF calculation
  - to be utilized for on-line Dyno testing, and
  - may be implemented in the engine controller unit

Semi-empirical Model

Shayler's RGF Model

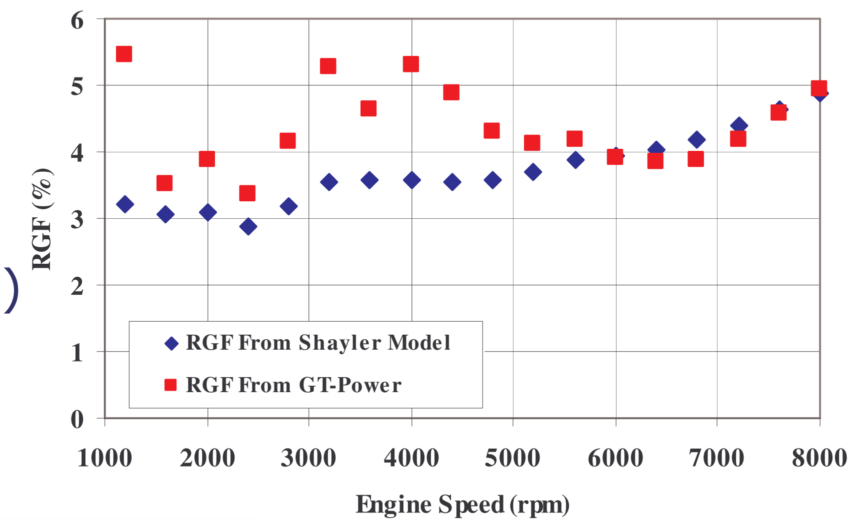
- IP: CR, VE, external EGR, intake/exhaust pressure ratio and A/F ratio

$$x_r = \frac{1}{(1+2(r_c - 1)\eta_v G)} \qquad G = \frac{(AFR + 1 - EGR)}{(AFR - AFR.EGR)}$$

C = f (Te/Tm); Here is called Density modifier

Te: exhaust runner temperature,

Tm: intake runner temperature = f (RPM, load)

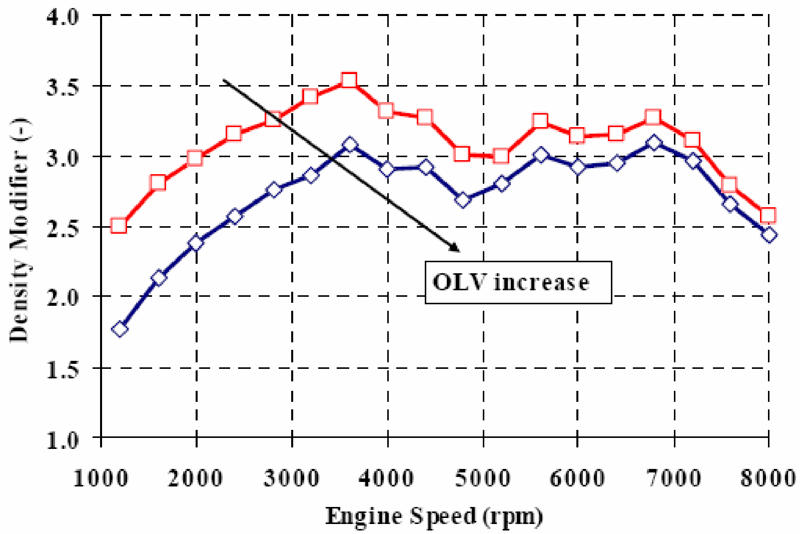


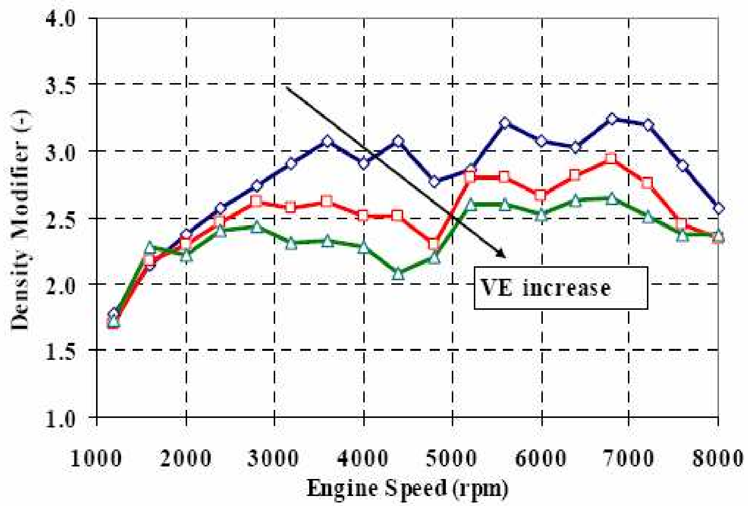
Fictitious or pseudo EGR ratio

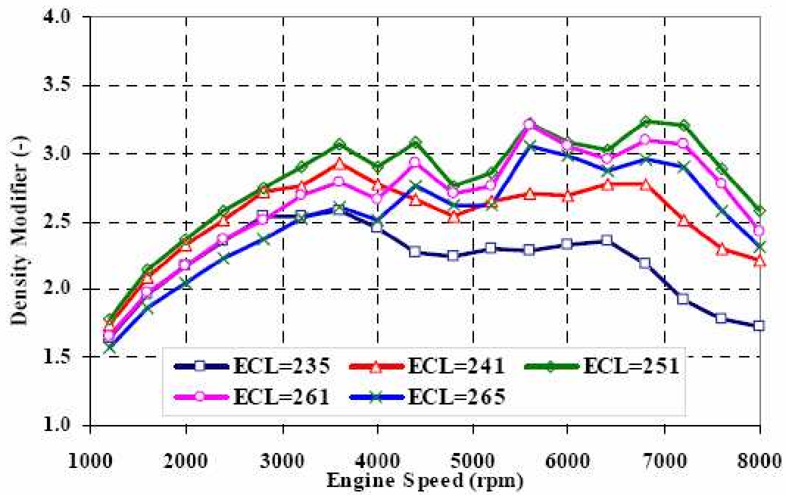
$$\text{EGR}= \frac{fn(OL)}{\dot{m}_a + fn(OL)} \qquad fn(OL) = 2.6\times 10^{-7}(OL)^2 - 7.1\times 10^{-7}(OL) - 5.1\times 10^{-5}$$

SAE 2000-01-1208

Effect of Parameters on Density Modifier

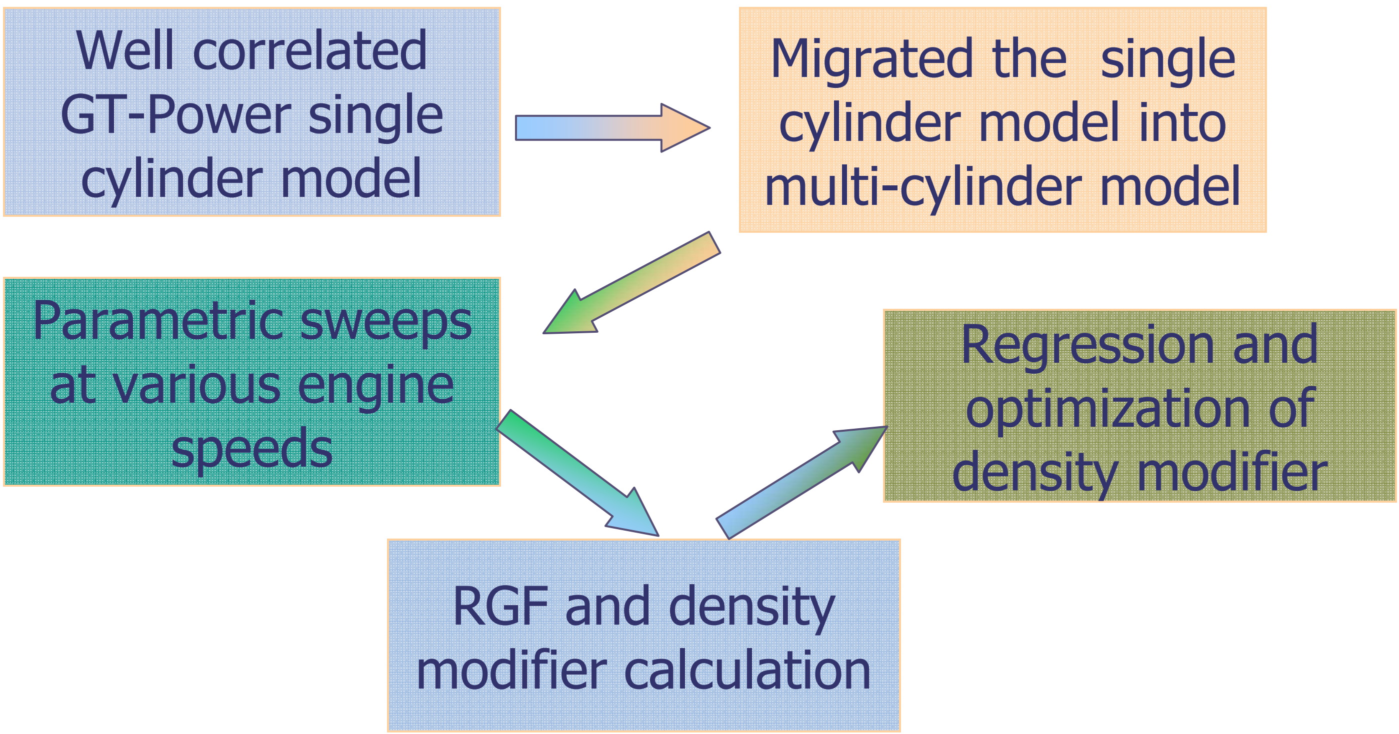




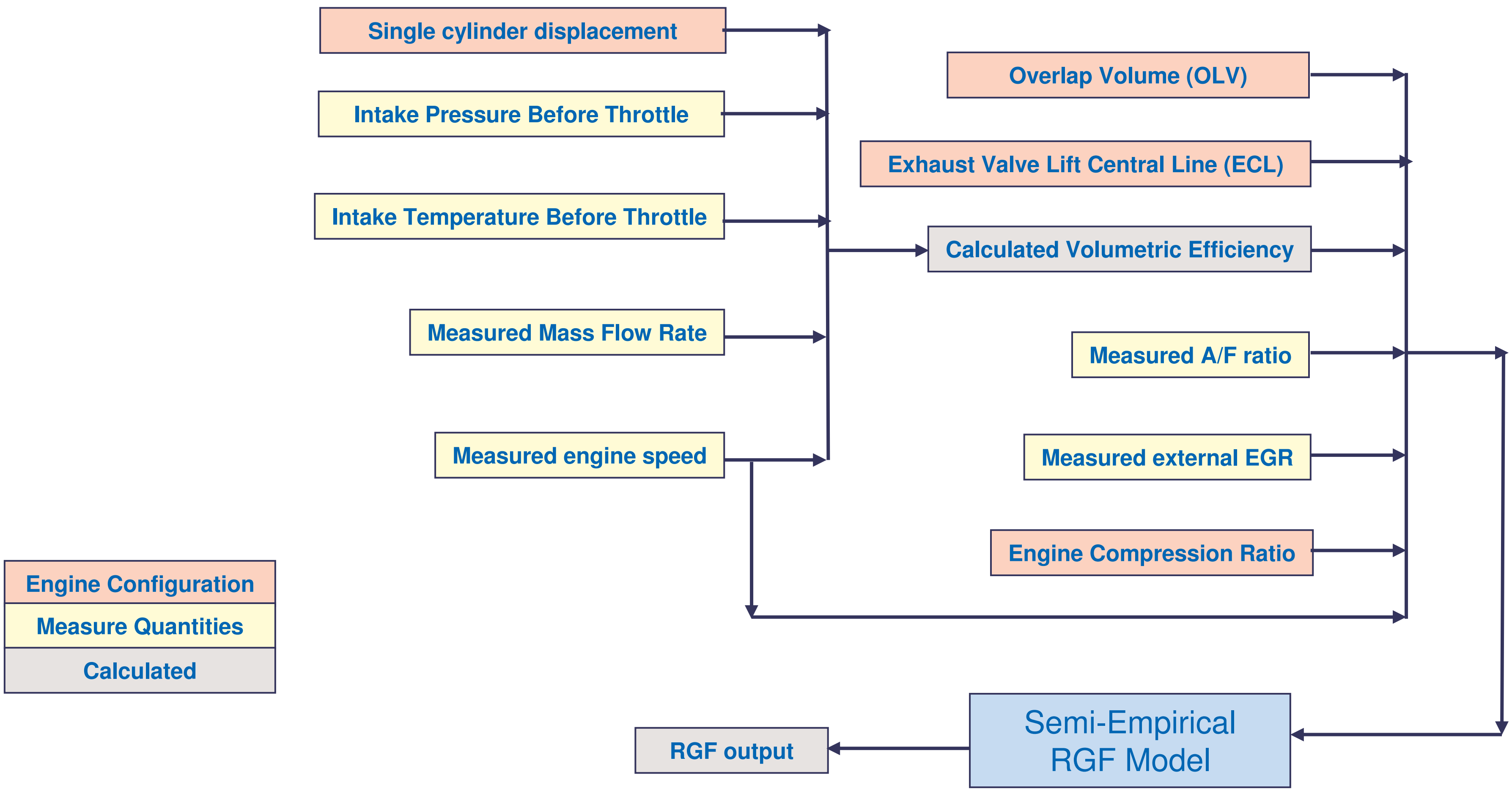


Approach

- Density modifier is not constant but a function of engine speed, overlap volume or angle, volumetric efficiency and exhaust central line (ECL)
- RGF calculated by GT-Power will be used as a reference



RGF Calculation Flow Chart

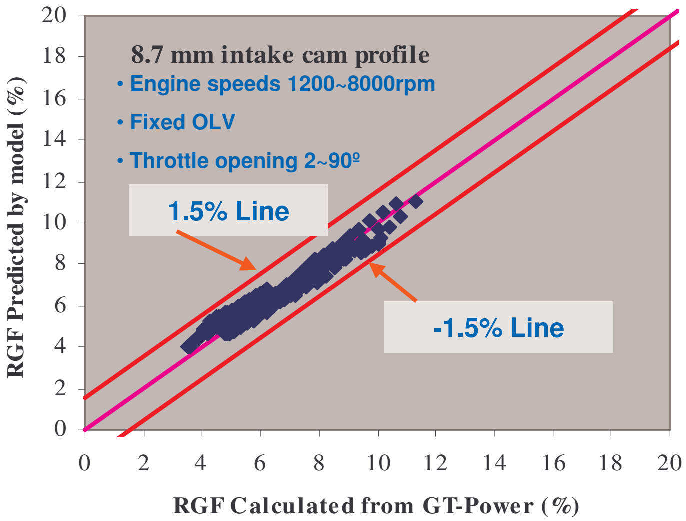


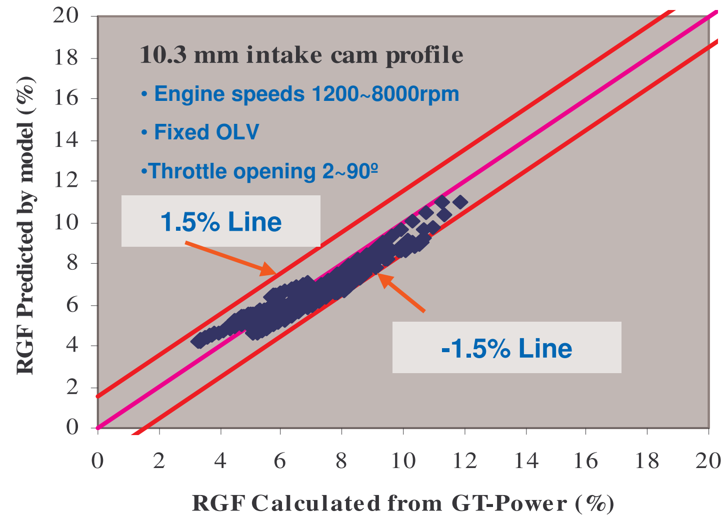
Calculation Interface in EXCEL

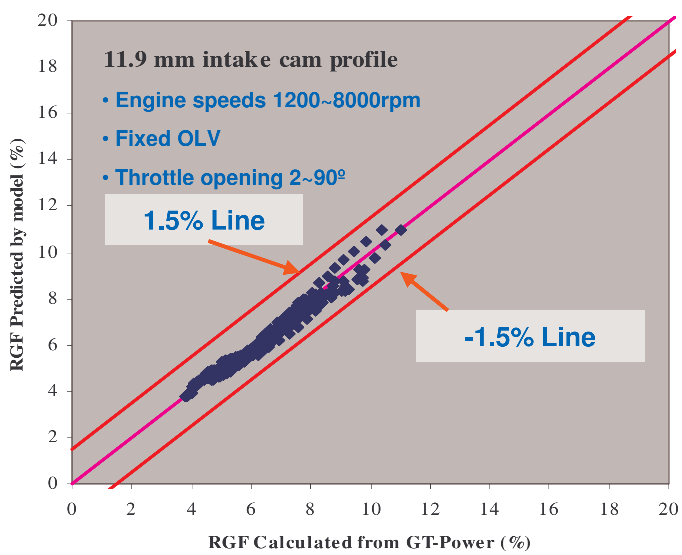
RGF Prediction With Semi-Empirical Model

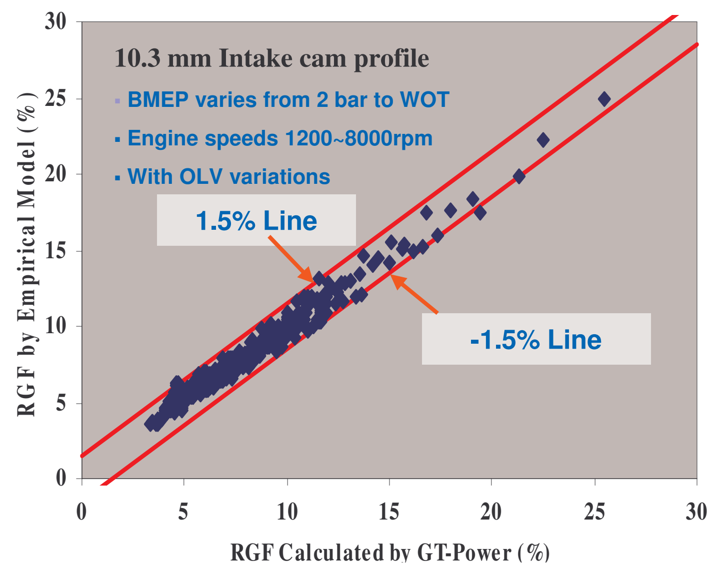
Test No.	Engine Speed	OverLap Volume	Exhaust Valve Open	Exhaust Valve Close	Air/Fuel Ratio	Cylinder swept volume	Intake pressure bef. Throt	Intake Temp. bef. Throt	Mass flow rate	Volumetric Efficiency	External EGR	Residual Gas Fraction
	[rpm]	[$cm^{2\cdot\circ}/L$]	[°]	[°]	[-]	[Liter]	[bar]	[°C]	[Kg/hr]	[-]	[%]	[%]
1	2001.1	14.91	128.0	392.0	14.1141	0.6735867	0.966	25	11.96	0.2620	0	15.47
2	1999.8	14.91	128.0	392.0	15.51	0.6735867				0.2767	0	14.87
3	1999.9	14.91	128.0	392.0	16.9764	0.6735867				0.2962	0	14.11
4	2000.6	14.91	128.0	392.0	17.8929	0.6735867				0.3084	0	13.66
5	2000.5	14.91	128.0	392.0	18.4146	0.6735867				0.3164	0	13.39
6	1600.1	14.91	128.0	392.0	14.5525	0.6735867				0.2940	0.257	14.95
7	1600	14.91	128.0	392.0	14.437	0.6735867				0.2936	5.241	14.36
8	1599.7	14.91	128.0	392.0	14.45144	0.6735867				0.2901	9.261	14.04
9	1599.5	14.91	128.0	392.0	14.45144	0.6735867				0.2897	12.605	13.64
10	1600.2	14.91	128.0	392.0	14.307	0.6735867				0.2903	14.257	13.39
11	2000	14.91	128.0	392.0	10.638	0.6735867				0.677	33.848	4.54
12	3000	14.91	128.0	392.0	10.638	0.6735867				0.746	36.964	4.26
13	3999.5	14.91	128.0	392.0	10.417	0.6735867				0.794	41.269	4.12
14	3999.9	14.91	128.0	392.0	10.417	0.6735867				0.793	43.560	3.97
15	4500.1	14.91	128.0	392.0	10.309	0.6735867				0.760	43.992	3.66
16	1999.8	14.91	128.0	392.0	12.048	0.6735867				0.315	25.186	10.33
17	1999.8	14.91	128.0	392.0	12.048	0.6735867				0.393	32.794	7.73
18	2000	14.91	128.0	392.0	12.048	0.6735867				0.546	34.911	5.56
19	2000.2	14.91	128.0	392.0	11.905	0.6735867				0.802	35.499	3.38
20	602.8	14.91	128.0	392.0	11.905	0.6735867				0.179	35.567	20.49
21	600.6	14.91	128.0	392.0	11.905	0.6735867				0.168	35.307	21.71
22	600.3	14.91	128.0	392.0	11.905	0.6735867				0.164	35.331	22.12
23	599.9	14.91	128.0	392.0	12.048	0.6735867				0.157	35.621	22.77
24	599.9	14.91	128.0	392.0	12.048	0.6735867				0.158	35.524	22.73
25	600	14.91	128.0	392.0	12.195	0.6735867				0.158	35.750	22.70
26	601.3	14.91	128.0	392.0	12.195	0.6735867				0.158	35.245	22.76
27	600.9	14.91	128.0	392.0	12.346	0.6735867				0.168	35.527	21.68
28	1600	14.91	128.0	392.0	14.491	0.6735867	0.976	32	10.948	0.304	0	13.99
29	1600	14.91	128.0	392.0	14.491	0.6735867	0.976	32	10.692	0.297	5.370	13.71
30	1599.2	14.91	128.0	392.0	14.361	0.6735867	0.976	32	10.475	0.291	10.909	13.32

Model Validation – Various Conditions

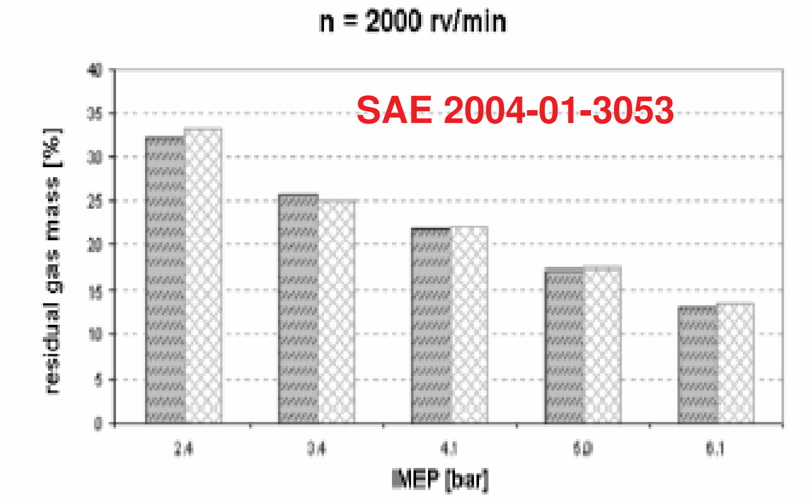




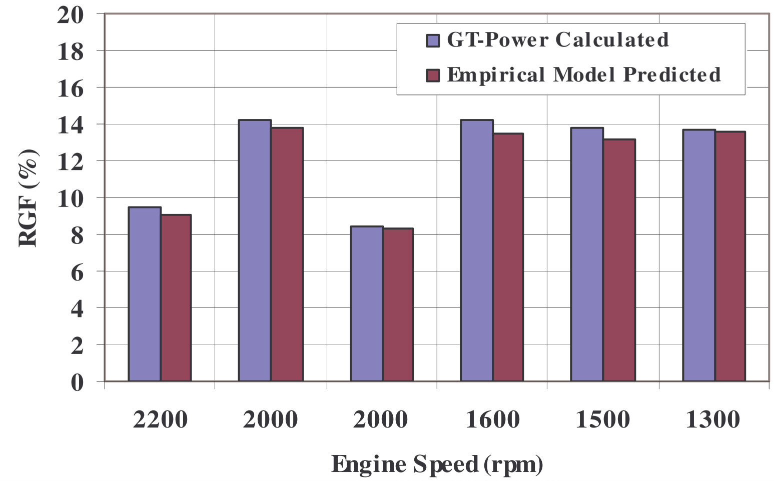


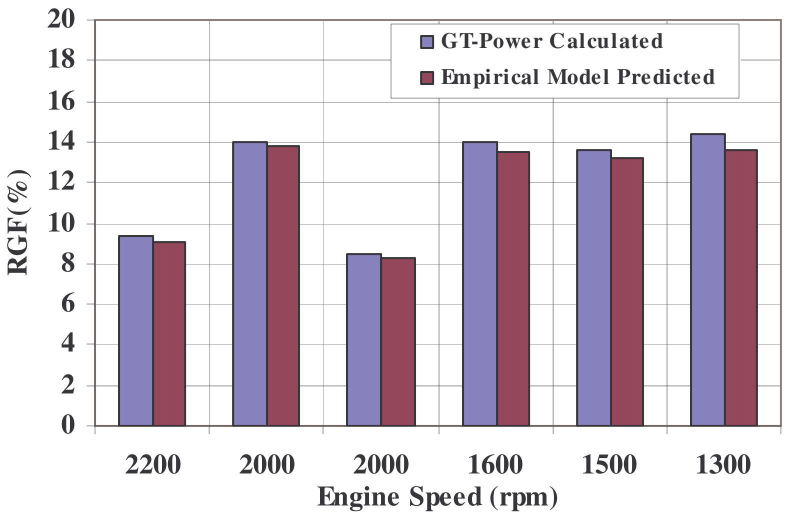


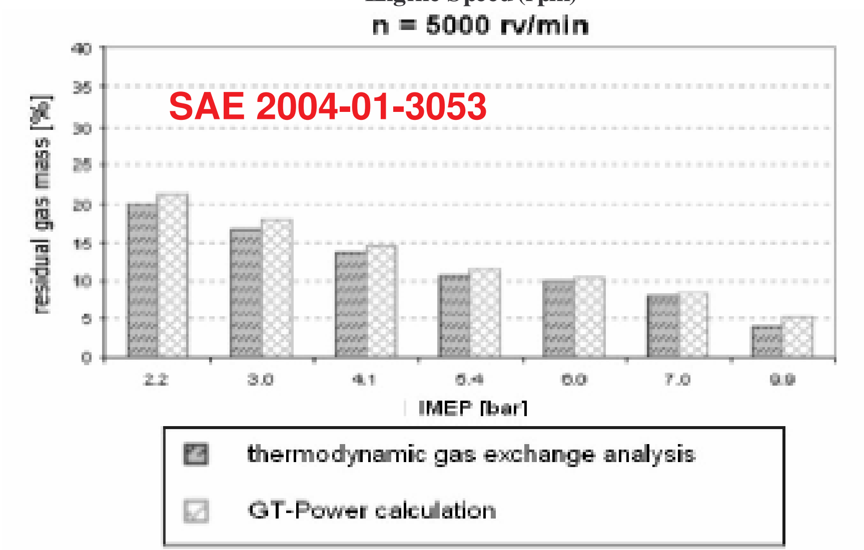
RGF Prediction at Part Throttle (PT)



POR Exhaust manifold







Log-style exhaust manifold

FEV

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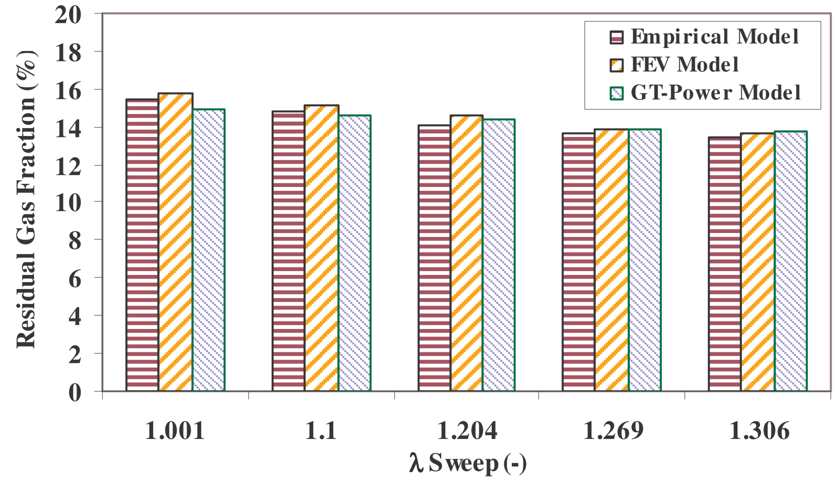
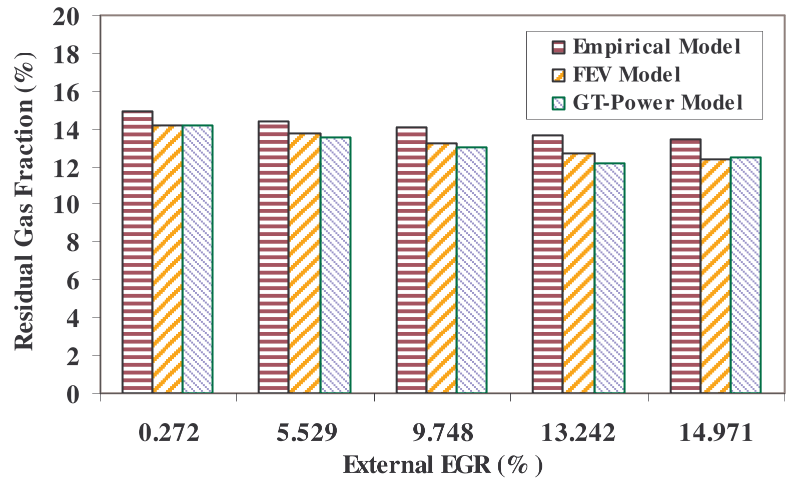
RGF Prediction – Single Cylinder

λ sweep with no external EGR head "B" at 2000rpm and 2.6 bar NMEP

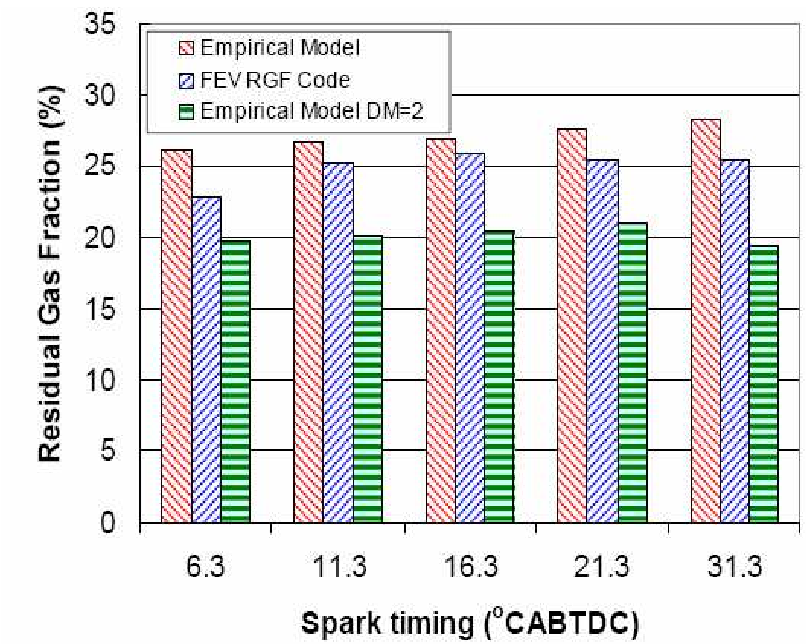


External EGR sweep with fixed λ and head "B" at 1600rpm/2.94 bar NMEP

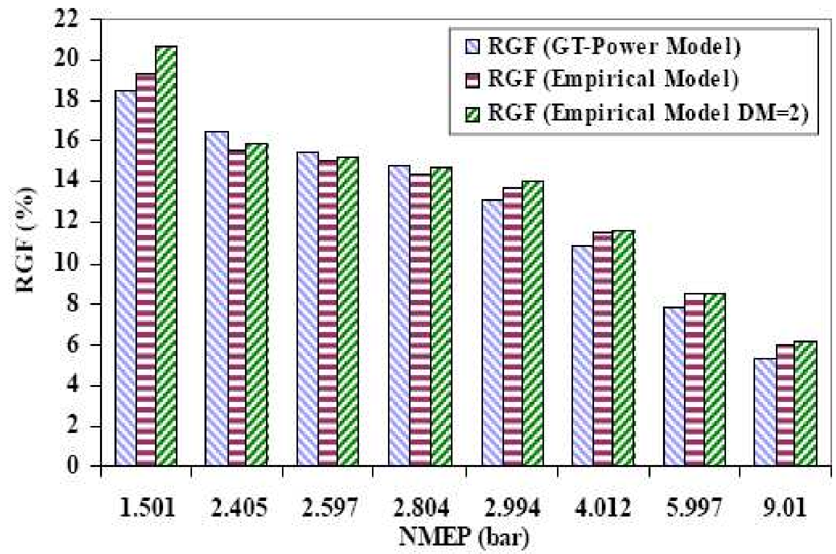


Reference: SAE 2006-01-3236, "A Semi-Empirical Model for Fast Residual Gas Fraction Estimation in Gasoline Engines"

RGF Prediction – Single Cylinder



600 RPM idle Spark Sweep



2000 RPM Load Sweep

Conclusions

- A GT-Power model with SITurb sub-model is very helpful to predict engine fuel economy and engine load with various combustion chamber geometries
- A well-calibrated GT-Power model is a very effective tool to predict/calculate RGF in cylinder, which was used as a reference to develop an empirical RGF model
- The empirical model was validated against GT-Power model calculation for various intake valve lift profiles, overlap volumes and engine speeds
- The empirical model was also compared against the FEV approach (utilizing a single cylinder test data) for various part throttle and WOT conditions
- The empirical model was embedded in Excel and maybe used for both off-line, on-line and real time RGF calculations
  - It was later validated on a small I4 turbo-charged engine

Thank You!