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New Technology Research & Development Program
Grant Contract 582-5-65591-0007

Task 5 Deliverable Report

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Task #5
EGR Mapping for 60-70% NOx Reduction
(Old Tasks #5 & 6)

CAT 3406B Diesel Engine

Contract No. 582-5-65591-0007

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EGR Mapping & Strategy

This report summarizes the EGR Mapping Test results as performed on the CAT 3406B engine utilizing a PTO dynamometer and testing instrumentation at CTI's facilities in Michigan Center, Michigan.

The EGR system developed by CTI is based on the "low-pressure loop EGR" concept. This strategy has few advantages when compared to the "high-pressure loop EGR" concept used mostly on OEM applications. Primary advantages are lower fuel consumption, clean up of particulate matter from EGR exhaust through particulate converter and cooler exhaust gases lending to higher heat absorbing capacity for similar exhaust flow rate. In summary, the low-pressure loop strategy has few primary advantages, and is considered practical in retrofit applications.

This report highlights the basic strategy for performing mapping tests. Simply, the AVL 8-mode has been selected as a base for EGR mapping. The 8-mode, defined as a steady-state engine operating conditions as a function of engine rate torque, and RPM can predict with a reasonable degree of accuracy the NOx emission reduction during Federal transient emission testing. The basis for the 8-mode definitions weighing factors for the CAT 3406B engine is outlined in this report.

Strategy for the 60-70% NOx reduction is based on selecting an EGR injection ratio that generates the maximum NOx reduction provided that the fuel penalty is less than 5% for each mode. Additional care is given to reduce EGR injection at or close to full load condition since the adverse affect of EGR becomes more pronounced in terms of power loss and excessive visible emissions. A summary report for the 60-70% NOx reduction strategy is outlined in Attachment 1. The attachment illustrates the mapping results for each mode, selected injection strategy (test no.), calculation of fuel rates & penalty, calculation of mass emissions, and calculations of composite AVL NOx reduction.

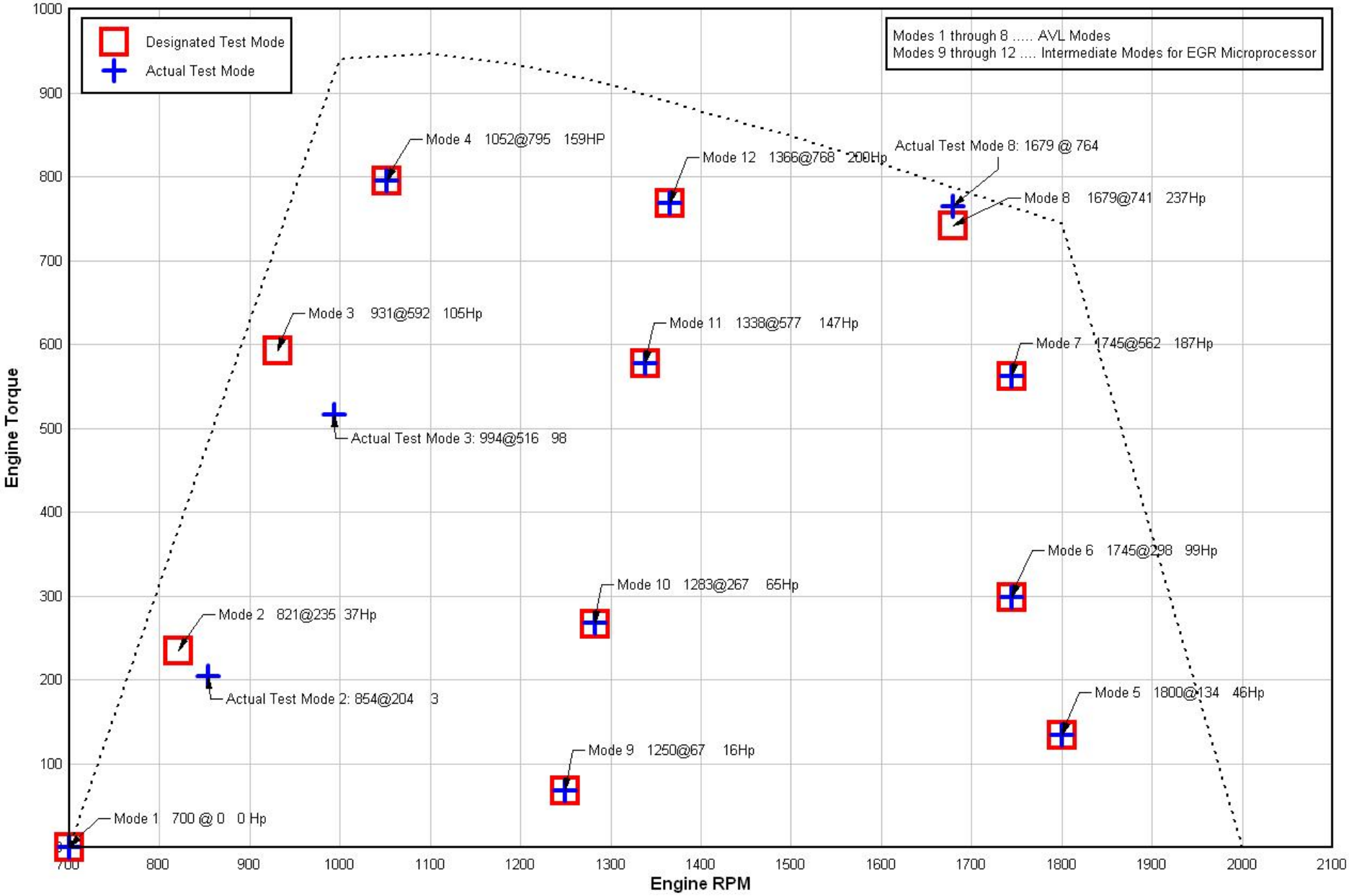
Since the stated goal of this project is to achieve the highest reduction in NOx without allowing fuel penalty to exceed 5%, the results of this mapping are selected as the basis for the implementation strategy. Strategy for 50-60% reduction is based on selecting an EGR injection ratio that generates maximum NOx reduction, but with greater emphasis on minimizing fuel penalty and capitalizing on certain EGR injection rate at certain engine modes that produce negligible fuel penalty, or in isolated modes can result in an increase in fuel economy. A summary report for the 50-60% NOx reduction strategy is outlined in Attachment 2. This report is similar to the one in Attachment 1, but the EGR

injection strategy is different. The results from this strategy will not be used in this project. However, due to the relatively high NOx reduction and low fuel economy, this strategy could be used in future EGR applications.

The selected strategy will be used on the new CAT 3126 engine. To that extent, verification of EGR mapping for each mode will be performed on-the-road during durability testing. The EGR injection strategy could be fine-tuned as a result of on-the-road results. Otherwise, it would be the same, but with ratings (torque, RPM) normalized to the CAT 3126 engine.

8-Mode AVL Test Points and 4 Intermediate Test Points

For the CAT 3406B Engine, 1985 Model Year, Engine Serial No. 4MG30908, OEM No. E8HS-6007-CDEAB



Dynamometer RPM and Torque Determination from AVL 8 Mode and Engine Torque Curve

Cat 3406B Diesel-Example Data (not real)

Hand Enter all Data in Yellow Highlight!

Mfg Engine Idle RPM	700
Mfg Engine Rated RPM	2100

Torque Curve Coefficients Enter here →→→→	Torque = a*RPM^4 + b*RPM^3 + c*RPM^2 + d*RPM + e				
	a	b	c	d	e
	6.00E-11	-3.00E-07	5.00E-04	-3.14E-01	8.73E+02

example only! Not real torque curve data!

						Normalized Mode Data		Engine Data		Dyno Test Points	
	Mode	Weight Factor (wf)	Transm Gear Ratio	Transm Efficiency	Maximum Torque @ RPM	% Engine RPM	% Load	Engine RPM	Engine Torque	Dyno RPM	Dyno Torque (ft-lb)
AVL 8 Mode Data Set	1	35	1.2	0.98	810	0	0	700	0	583	0
	2	6.34	1.2	0.98	814	11	25	854	204	712	239
	3	2.91	1.2	0.98	819	21	63	994	516	828	607
	4	3.34	1.2	0.98	822	32	84	1148	690	957	812
	5	8.4	1.2	0.98	807	100	18	2100	145	1750	171
	6	10.45	1.2	0.98	805	95	40	2030	322	1692	379
	7	10.21	1.2	0.98	805	95	69	2030	555	1692	653
	8	7.34	1.2	0.98	805	89	95	1946	764	1622	899
Blend Points for Smoothing Between the AVL 8 Mode Mapping Points	9	n/a	1.2	0.98	820	25	25	1050	205	875	241
	10	n/a	1.2	0.98	820	50	25	1400	205	1167	241
	11	n/a	1.2	0.98	809	75	25	1750	202	1458	238
	12	n/a	1.2	0.98	820	25	50	1050	410	875	482
	13	n/a	1.2	0.98	820	50	50	1400	410	1167	482
	14	n/a	1.2	0.98	809	75	50	1750	405	1458	476
	15	n/a	1.2	0.98	820	50	70	1400	574	1167	675
	16	n/a	1.2	0.98	809	75	70	1750	567	1458	666
	17	n/a	1.2	0.98	820	50	90	1400	738	1167	868
	18	n/a	1.2	0.98	809	75	90	1750	728	1458	857

----------Definitions----------

Mode Mode numbers 1-8 as defined by AVL 8 Mode test. The modes describe Normalized RPM, Normalized .Torque and the Weight Factors to match USA HD Transient FTP Test. Modes 9-18 are not part of AVL 8 Mode and are used during engine mapping to "smooth" EGR Demand table over the entire engine operating range.

Weight factor These weight factors used with emissions data to give correct bias to each mode. Mass emissions will equate roughly to an engine operating on USA HD Transient FTP

Transm Gear Ratio Transmission gear ratio. (Assumes no torque conv slip!) Defined as: EngineRPM/Transmission Shaft Output RPM. (Use 1.0 if no transmission is used!)

Transm Efficiency Enter a measured or assumed power efficiency across the transmission. Use 0.98 for a manual transmission fixed gear. Use 0.95 for an automatic transmission in fixed gear.

Maximum Torque @ RPM Calculated from 4th order polynomial curve fit of full power engine torque curve.

% Engine RPM Normalized engine rpm. Idle RPM is defined as 0%. Rated Speed is defined as 100%.

% Load % of full power Torque for each Mode. This is related to the corresponding %Engine RPM

Engine RPM De-normalized Engine Torque based on Normalized % Load and Torque Curve fit @ each RPM.

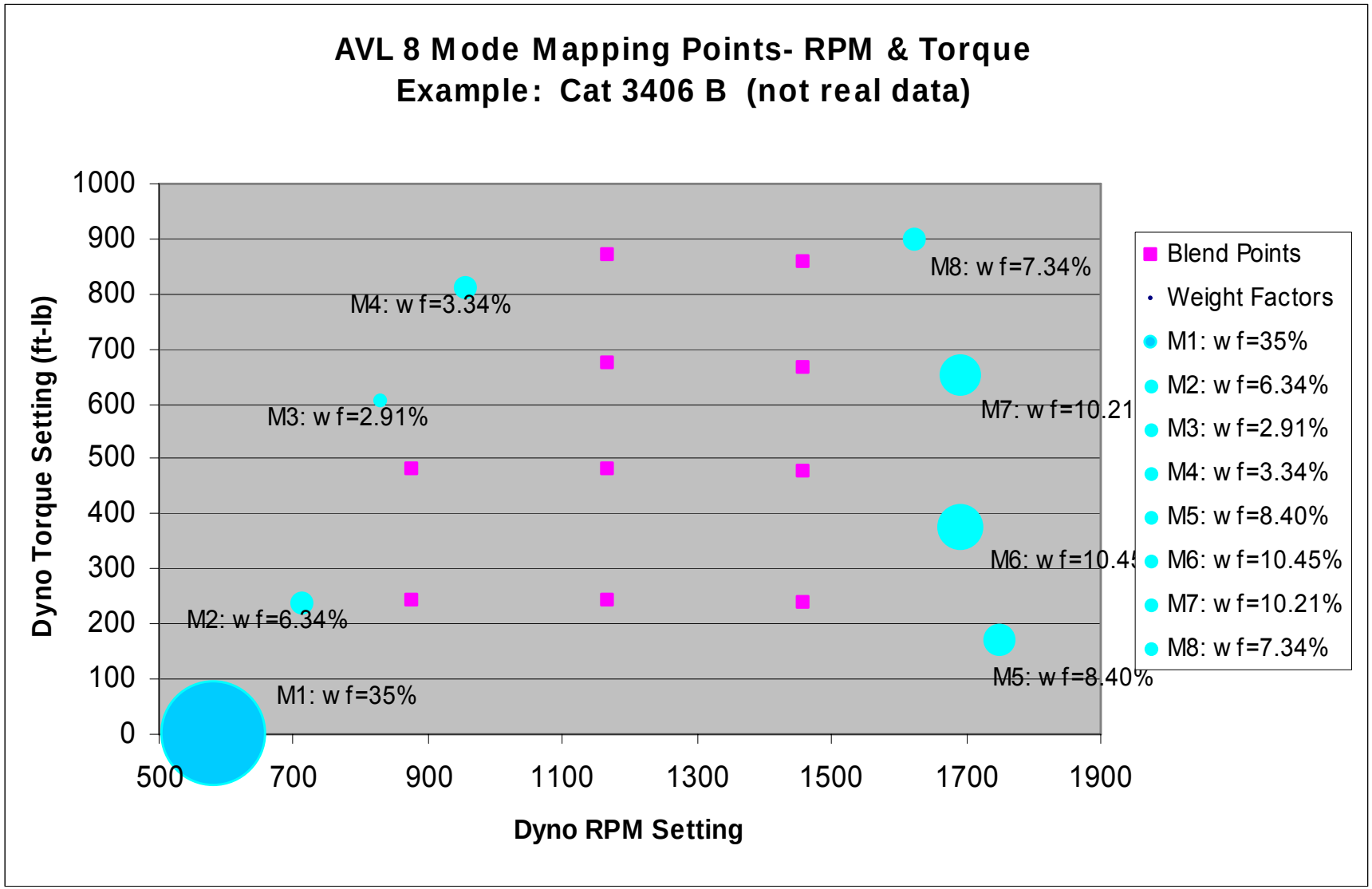
Engine Torque De-normalized Engine RPM based on engine manufacturer Idle RPM, Rated RPM and Mode Normalized Engine RPM

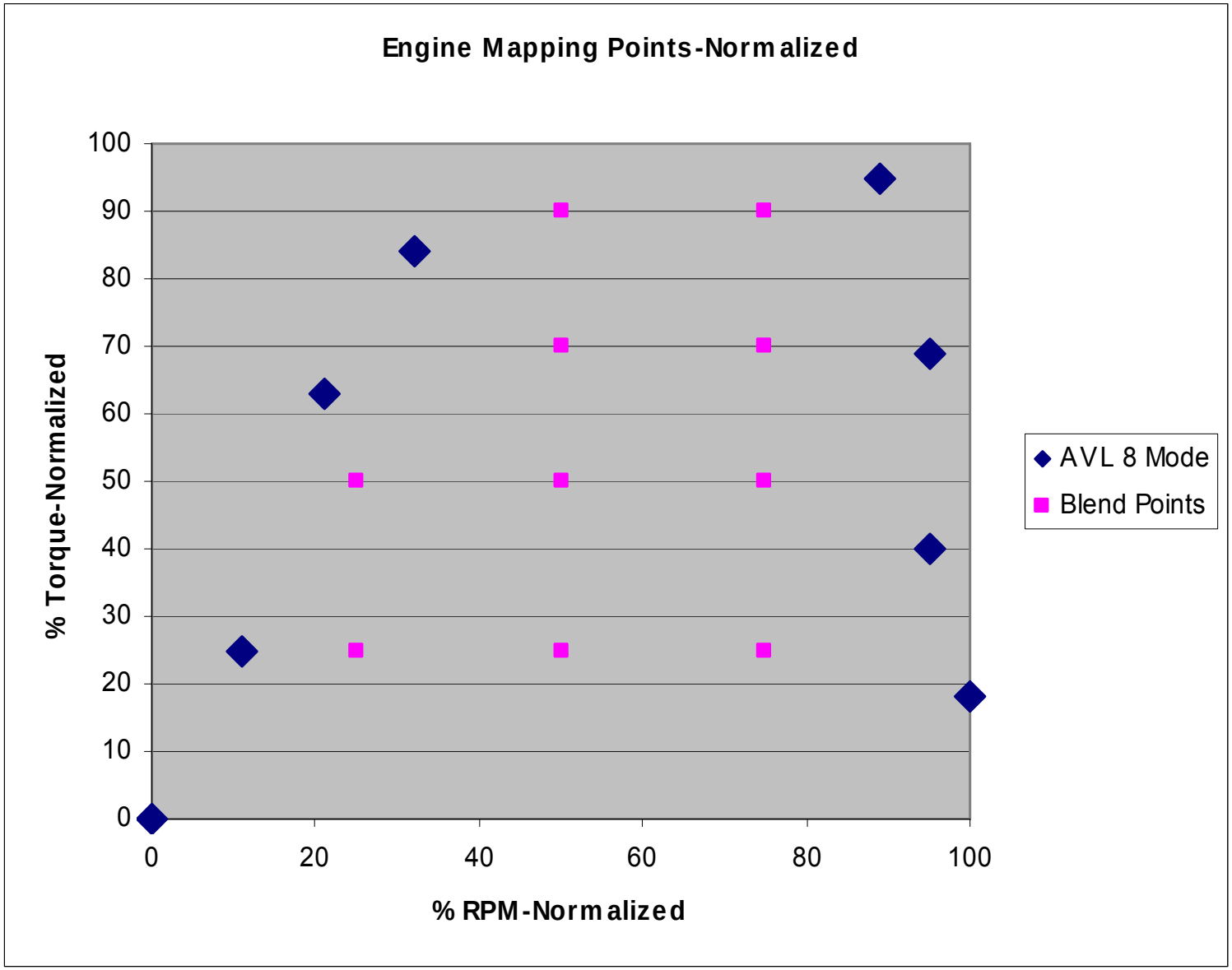
Dyno RPM RPM to set at dynamometer. Accounts for Trans Gear Ratio.

Dyno Torque Torque (ft lb) to set at dynamometer. Accounts for Trans Gear Ratio (increases dyno torque) and Trans Efficiency (decreases dyno torque).

Weighted Emission Results Weight Factors are applied to each Emission Gas mass flow and divided by the weighted power. All 8 Modes are summed

Example: CO (g/h), P(hp) $CO_{Mode1\text{-}8}$ CO (gram per hp-hour) = $(CO_1*wf_1 + CO_2*wf_2 + CO_3*wf_3 \ldots\ldots CO_8*wf_8) / (P_1*wf_1 + P_2*wf_2 + P_3*wf_3 \ldots\ldots CO_8*wf_8)$


AVL 8 Mode Mapping Points- RPM & Torque
Example: Cat 3406 B (not real data)
Dyno Torque Setting (ft-lb)
1000
900
800
700
600
500
400
300
200
100
0
500
700
900
1100
1300
1500
1700
1900
Dyno RPM Setting
M1: w f=35%
M2: w f=6.34%
M3: w f=2.91%
M4: w f=3.34%
M5: w f=8.40%
M6: w f=10.45
M7: w f=10.21
M8: w f=7.34%
Blend Points
Weight Factors
M1: w f=35%
M2: w f=6.34%
M3: w f=2.91%
M4: w f=3.34%
M5: w f=8.40%
M6: w f=10.45%
M7: w f=10.21%
M8: w f=7.34%



Note: Blend Points for Modes 13-18 have not been included in the EGR Mapping Tests to reduce costs and time. The resulting impact was judged to be trivial in terms of the effect on the EGR electronic control system.

Calculation of Mass Emissions

for the CAT 3406B Engine, 1985 Model Year
Average of the Sum of weighted power and final NOx reductions
Engine Serial No. 4MG30908, OEM No. E8HS-6007-CDEAB

Mode (Baseline)	Mass Emission gms/hour	Weight Factor for AVL 8-Mode Heavy Duty Cycle (WF)	Mass Emission x Weight Factor	Mode (Selected) EGR	Mass Emission gms/hour	Weight Factor for AVL 8-Mode Heavy Duty Cycle (WF)	Mass Emission x Weight Factor	NOx Reduction
1	13.2	35.00	460	1	2.2	35.00	75	83.65%
2	72.2	6.34	458	2	13.9	6.34	88	80.73%
3	182.2	2.91	530	3	50.7	2.91	147	72.19%
4	387.8	3.34	1,295	4	138.0	3.34	461	64.41%
5	150.6	8.40	1,265	5	39.8	8.40	334	73.57%
6	263.0	10.45	2,748	6	88.1	10.45	921	66.50%
7	577.3	10.21	5,895	7	144.7	10.21	1,478	74.93%
8	636.6	7.34	4,673	8	414.8	7.34	3,045	34.83%
		Σ Mass Emission x Weight Factor =	17,324			Σ Mass Emission x Weight Factor =	6,550	

Calculation of Average of sum of weighted power of the AVL 8-modes

Mode (Baseline)	Horse Power (HP)	Weight Factor for AVL 8-Mode Heavy Duty Cycle (WF)	HP x WF	Mode (Selected) EGR	Horse Power (HP)	Weight Factor for AVL 8-Mode Heavy Duty Cycle (WF)	HP x WF
1	0	35.00	0	1	0	35.00	0
2	32	6.34	203	2	32	6.34	203
3	95	2.91	276	3	95	2.91	276
4	160	3.34	534	4	158	3.34	528
5	46	8.40	386	5	46	8.40	386
6	101	10.45	1,055	6	102	10.45	1,066
7	181	10.21	1,848	7	188	10.21	1,919
8	234	7.34	1,718	8	234	7.34	1,718
		Σ HP x WF =	6,021			Σ HP x WF =	6,096

$$\text{Baseline AVL Composite Brake Specific Emission} = \frac{\Sigma \text{ Mass Emission x Weight Factor}}{\Sigma \text{ HP x WF}} = 2.88 \text{ gms/bhp.hr}$$

$$\text{Selected Modes (EGR) Composite Brake Specific Emission} = \frac{\Sigma \text{ Mass Emission x Weight Factor}}{\Sigma \text{ HP x WF}} = 1.07 \text{ gms/bhp.hr}$$

$$\text{Composite AVL NOx Reduction} = \frac{(2.88-1.07)\text{x}100}{2.88} = 63\%$$

Note: The average NOx emission reduction of 63% is equivalent to that generated from EPA transient test procedures according to AVL.

Calculation of Fuel Rate & Penalty

for the CAT 3406B Engine, 1985 Model Year

Engine Serial No. 4MG30908, OEM No. E8HS-6007-CDEAB

Mode (Baseline)	Fuel Consumption gms/hr	Weight Factor for AVL 8-Mode Heavy Duty Cycle (WF)	Fuel Consumption x Weight Factor	Fuel Rate lbs/bhp.hr	Mode (Selected) EGR	Fuel Consumption gms/hr	Weight Factor for AVL 8-Mode Heavy Duty Cycle (WF)	Fuel Consumption x Weight Factor	Fuel Rate lbs/bhp.hr
1	5.2	35.00	181	-	1	4.5	35.00	158	-
2	17.6	6.34	111	0.548	2	18.0	6.34	114	0.563
3	43.4	2.91	126	0.457	3	46.4	2.91	135	0.489
4	68.6	3.34	229	0.429	4	71.8	3.34	240	0.449
5	33.7	8.40	283	0.733	5	37.1	8.40	311	0.806
6	55.9	10.45	584	0.554	6	60.4	10.45	631	0.592
7	92.8	10.21	947	0.513	7	98.4	10.21	1,005	0.523
8	102.6	7.34	753	0.438	8	103.6	7.34	760	0.443
		Σ Fuel Consumption x Weight Factor =	**3,216**				**Σ Fuel Consumption x Weight Factor =**	**3,354**	

$$\textbf{Fuel Penalty} = \frac{(\Sigma \text{ Selected Fuel Consumption x Weight Factor} - \Sigma \text{ Baseline Fuel Consumption x Weight Factor}) \times 100\%}{\Sigma \text{ Baseline Fuel Consumption}} = \mathbf{4.28\%}$$

Note: The fuel penalty calculated here in equivalent to that generated from EPA transient test procedure according to AVL.