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Heavy-Duty Natural Gas Engine Gas Composition Sensor

Development, Demonstration and Testing of Advanced Ultra-Low Emission Natural Gas Engines in Port Yard Trucks

CEC PIER Grant #PIR-16-016

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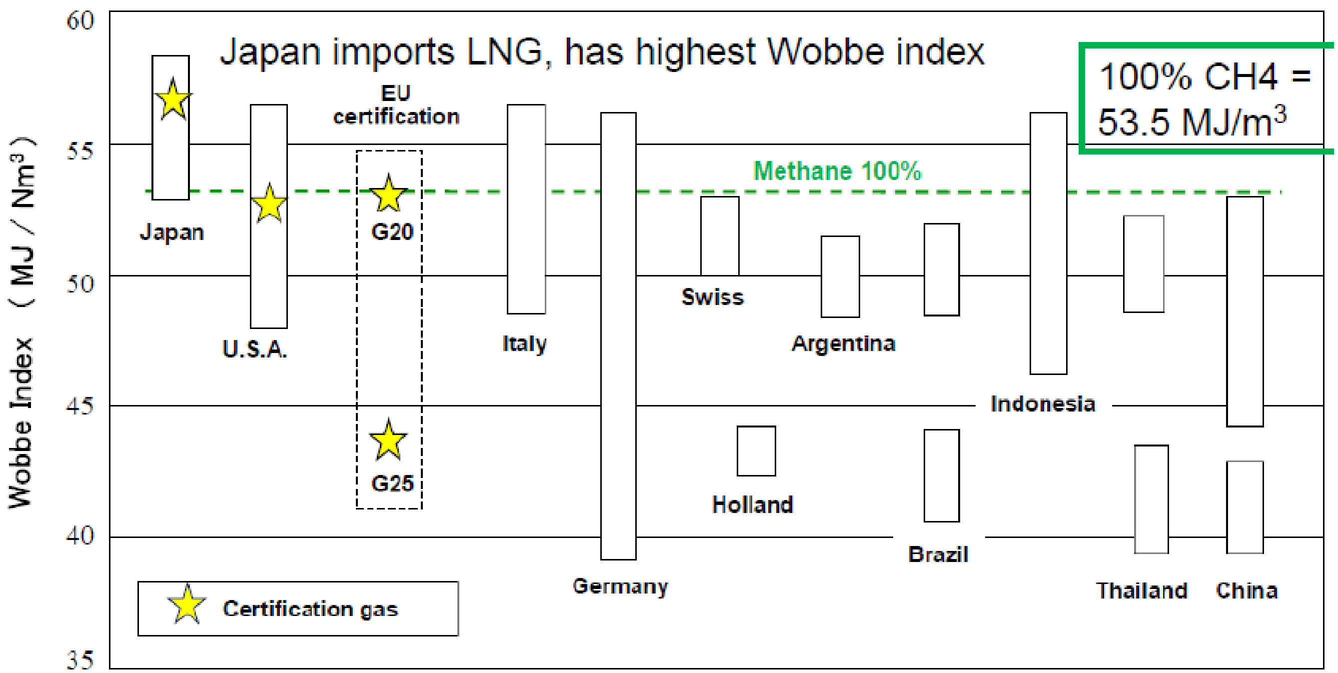
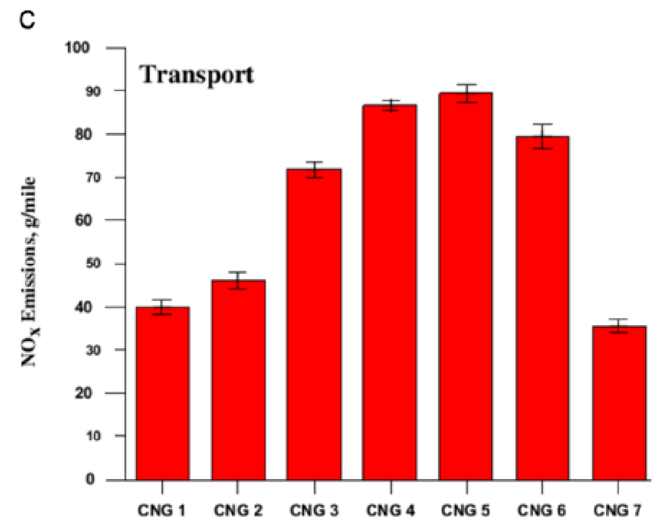
February 21, 2018

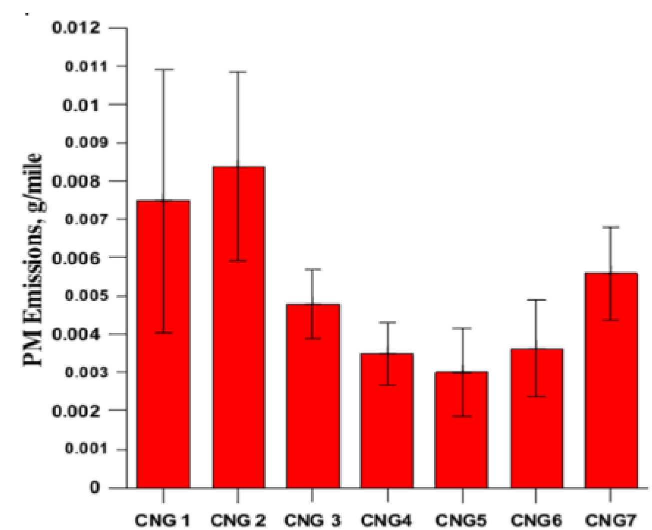
Background

Variable Natural Gas Fuel Properties Impacts Vehicle Emissions



Source: Masato Matsuki (Honda R&D Co.),'Study on Required CNG Qualities as an Automotive Fuel, as presented at ANGVA Conference, 28 November 2013

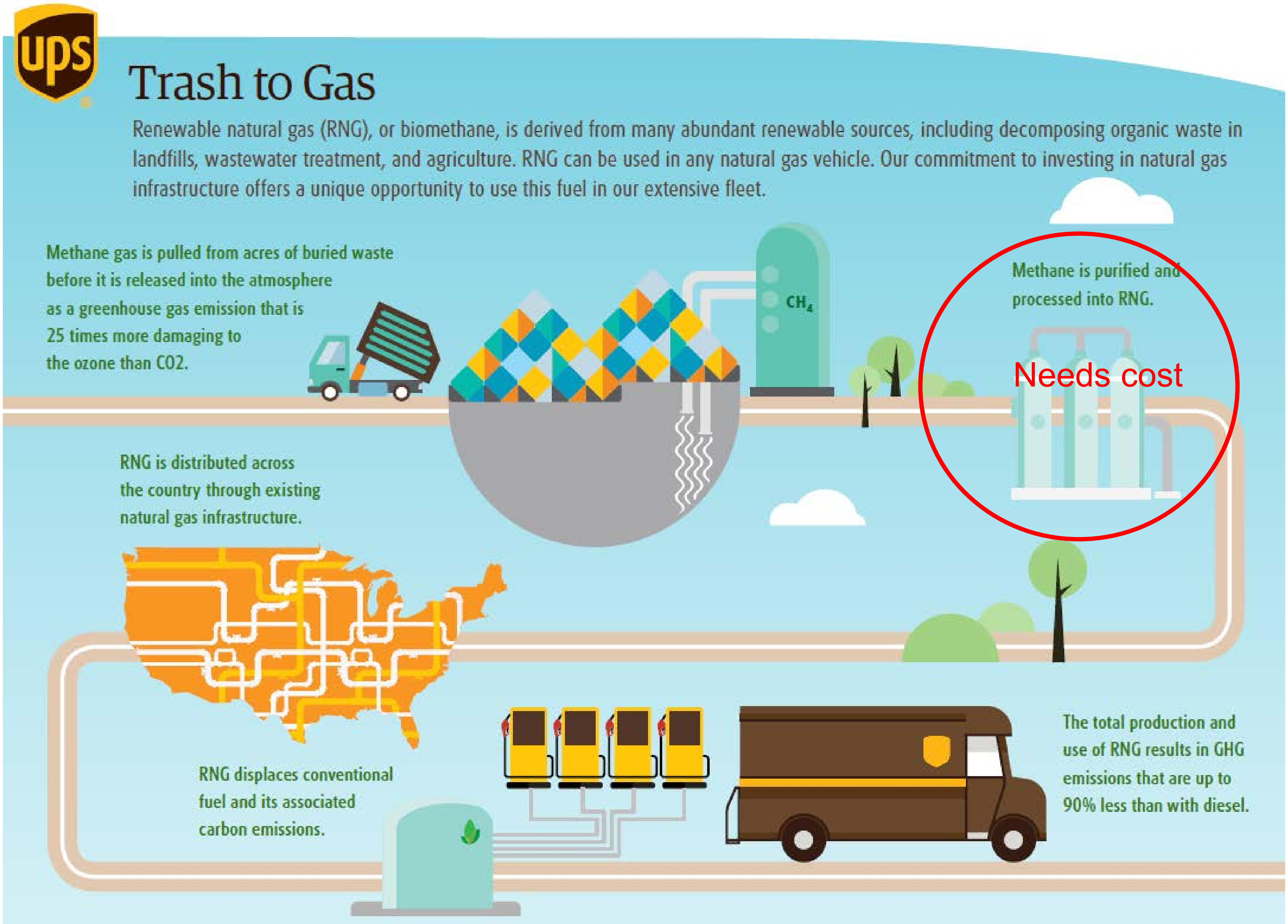




The influence of fuel composition on the combustion and emission characteristics of natural gas fueled engines

Renewable and Sustainable Energy Reviews 38 (2014) 64–78

RNG could have even higher variability in NG quality

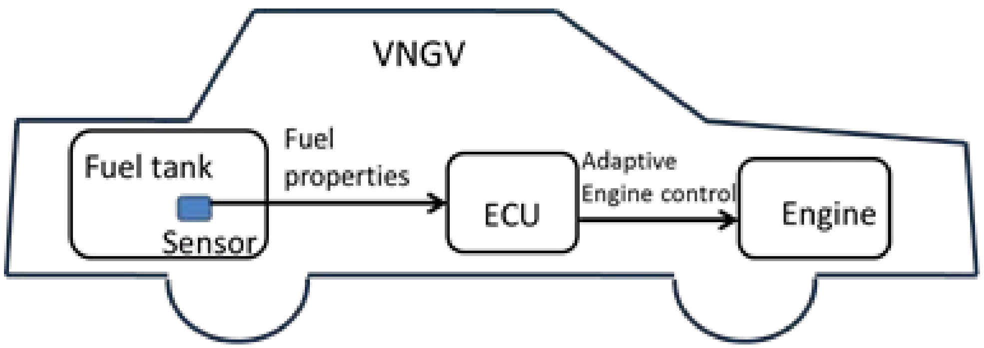


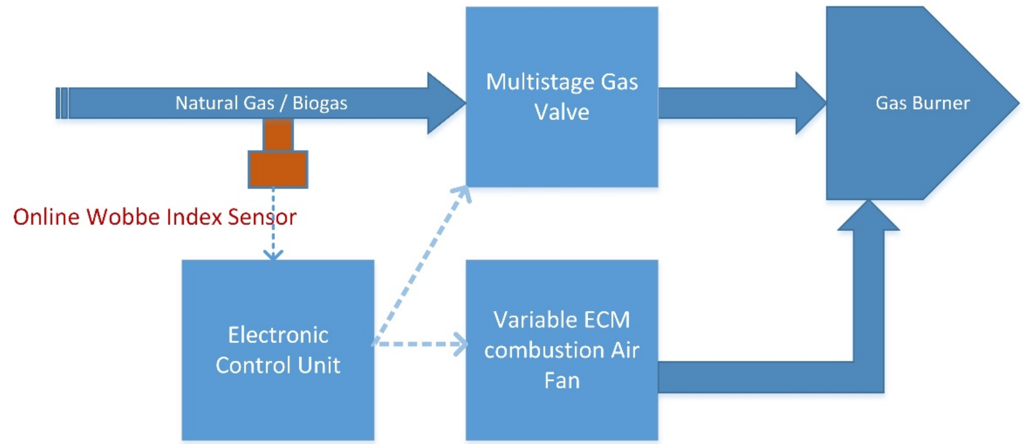
RNG May Not Need Complete Cleanup if NG Sensor Could Tune the Engine

Raw Biogas	Water Removal	Impurity (sulfide, siloxane)	CO_2 Removal	Compress	Gas grid
	Chiller/ Dryer	Adsorption / Filtration	water wash Scrubber PSA Membrane cryogenic	compressor	
Cost for $/mcf	~0.5	0.45~1.86	2.13 ~ 4.58	~1	

Source : www.rosrocaenvirotec.com &
Economic and Financial Aspects of Landfill Gas to Energy Project, CEC report

On-Line NG Sensing Could Provide Optimized Control





VNGA (Appliance)

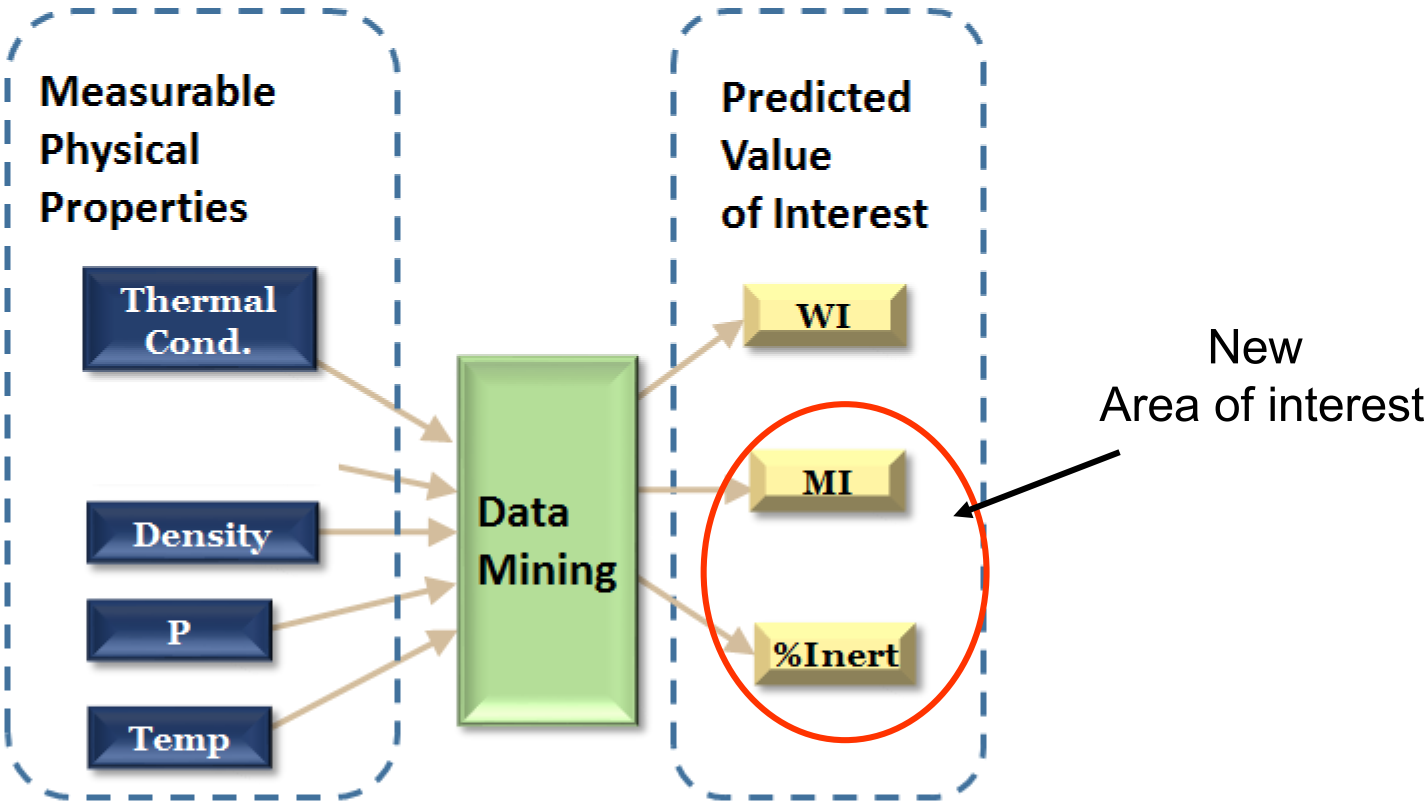
Conventional Wobbe Index Analyzer

The key enabling technologies For VNGV& VNGA

(1) On-board, real-time prediction of key fuel properties (such as Methane Index and Inert gas composition)

(2) Adaptive combustion control in the engine for a wide range of fuel variations.

Predictive Sensor by Data Mining: 2015 Design Wobbe Index



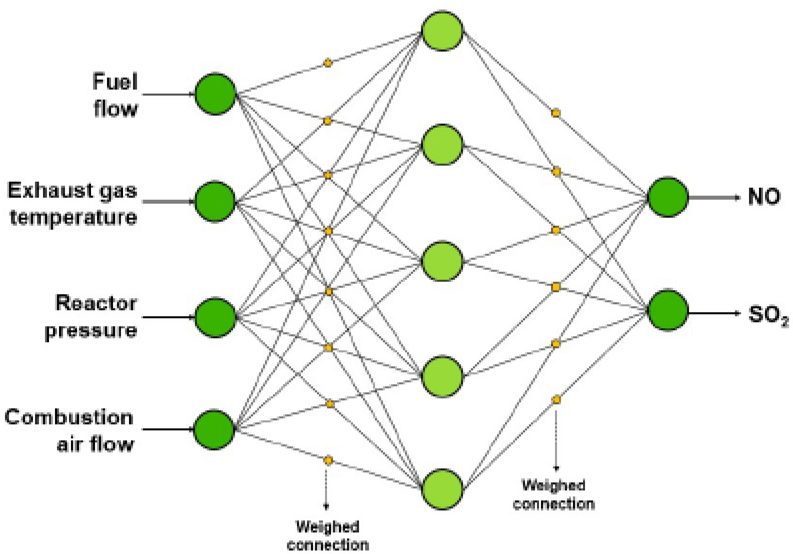
Article AT/ANALYTICAL/015–EN

Predictive emission monitoring systems
The power of software analyzers

Predictive Sensing by Data Mining is Not New

Gregorio Ciarlo, Federico Callero and Maurizio Simonelli, ABB SpA, Italy, discuss the application of predictive emission monitoring systems in applications when fuel characteristics are variable or in a complex process plant

Measurement made easy



http://www.continental-corporation.com/www/pressportal_com_en/themes/press_releases/3_automotive_group/powertrain/press_releases/pr_20110913_fuel_quality_sensor_en.html

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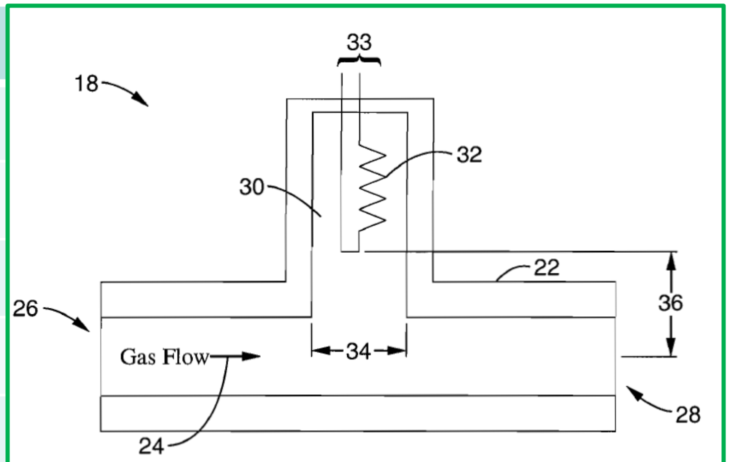
How Is It Done: Measure Physical Properties and Analyze for Trends

Thermal Conductivity : Property of a material to conduct heat
Very easy to measure by hot filament.

Gases	TC, mW/mK @ RT
H2	131.7
CO2	9.6
CH4	22.5
C2H6	11
N2	18.7



Hot wire TC sensor (right) and housing (left)

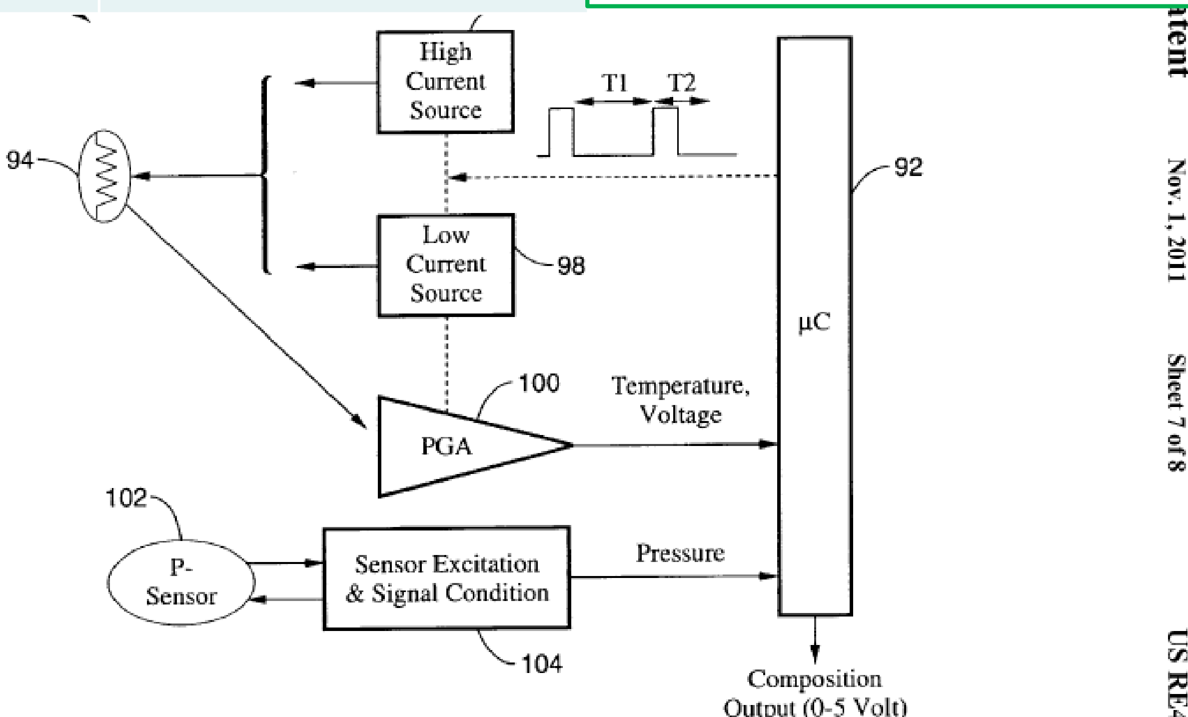


FIG. 9

Simultaneous Measuring T and TC from TC sensor, US patent RE42876E

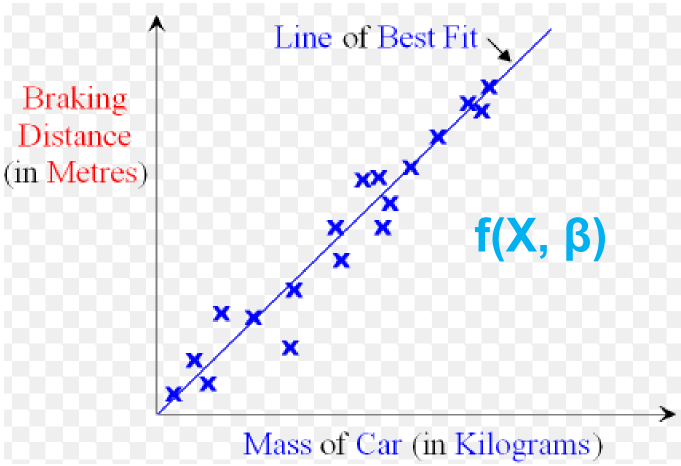
Data Mining

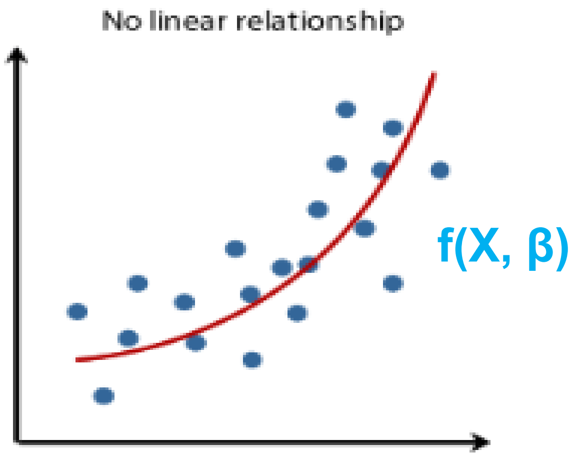
- **Data mining**
  - is a non-trivial process of identifying valid, novel, potentially useful, and ultimately understandable patterns both regularities and anomalies in data, and ultimately understanding the data. (i.e. extraction of meaning full information)

- **Major techniques**
  - Statistical methods
    - **Regression analysis**
    - **Multivariate analysis**
    - Many others
  - Machine leaning methods (AI based)
    - **Artificial neural network**
    - Decision tree induction
    - Many others
  - Pattern recognition
  - Visualization

Regression Analysis

X	Y
0.6	0.8
1.2	1.0
0.3	0.5
…	…





- **Goal**
  - Find relationships between independent variables (exploratory/predictor) and dependent variables (target/predicted)
  - **Result**: regression model, $f(X, \beta) = Y' \approx Y$ where X: independent variables; Y': predicted values; **Y**: target values; β: unknown parameters

Types of Regression Analysis

- **Simple regression**: $y=f(x)$
  - One dependent variable and one independent variable
- **Multiple regression**: $y=f(x_1, x_2, \ldots, x_n)$
  - One dependent variable and multiple independent variables that encompass linear and nonlinear
- **Multivariate regression**: $y_1, y_2, \ldots, y_m = f(x_1, x_2, \ldots, x_n)$
  - Multiple dependent variables and multiple independent variables (typically in matrices of variables)

Multivariate Analysis (MVA)

- **Goal**
  - Analyze multiple dependent and independent variables at once to find relationships among variables.
- **Four types of analysis from MVA**
  - Degree of relationship between variables
  - Significant differences between group means
  - Predicting membership in two or more groups from one or more variables
  - Explaining underlying structure

Multivariate Analysis Techniques

- Multiple regression
- Logistic regression
- Canonical correlation
- Factor analysis – data reduction
  – Principal components analysis (PCA)
- Multivariate Analysis of Variance (MANOVA)
  – Extension of Analysis of Variance (ANOVA)
- Discriminant function analysis (or classification)

We use Techniques in this color.

Example: Regression Analysis and MVA

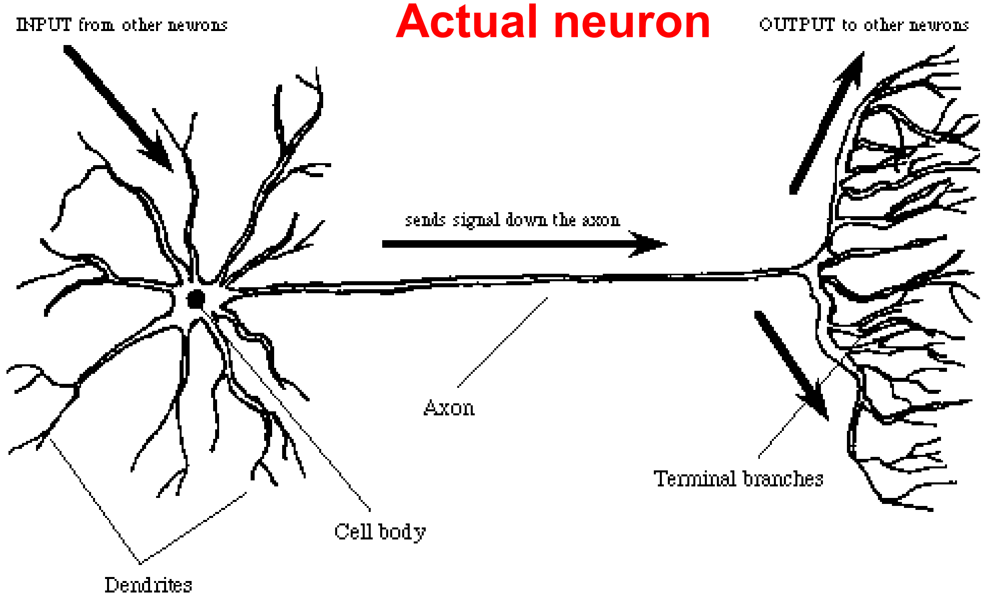
H_GPA	M_SAT	V_SAT	Sci_GPA	Univ_GPA
3.3	550	590	3.2	3.5
2.2	600	590	3.7	3.1
…	…	…	…	…

Variables	Description
H_GPA	High school GPA
M_SAT	Math SAT score
V_SAT	Verbal SAT score
Sci_GPA	Science GPA
Univ_GPA	Overall college GPA

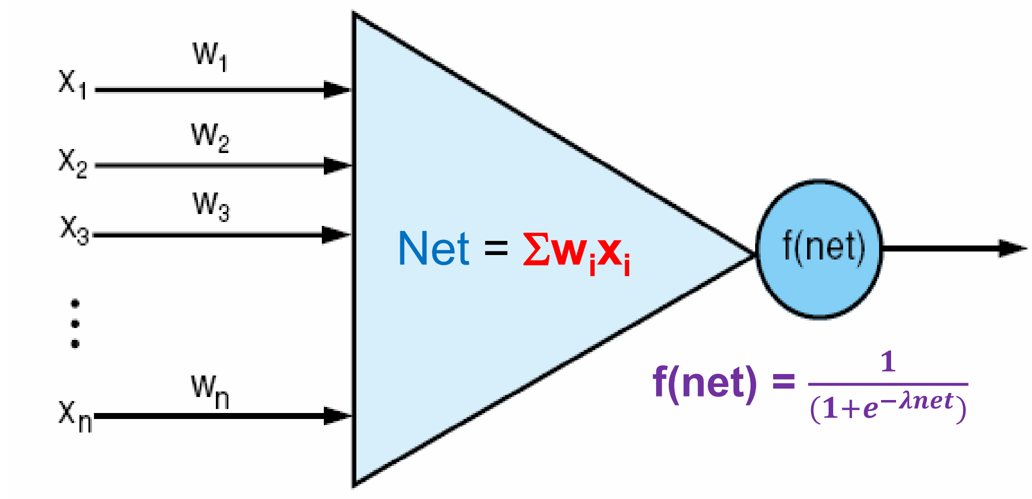
- **Some Questions** that can be answered
  - If a student had a 2.2 GPA in high school, what is the best estimated his/her college GPA? Regression analysis
  - What would you predict a student's overall college GPA if he/she received a 600 on the math and a 540 on the verbal portion of the SAT? Regression analysis
  - If a student's high school GPA is greater than 3.0, will the student receive the college GPA greater than 3.0? Regression analysis
  - What are all the key factors that influence the college GPA? MVA
  - What are all the key factors that influence the science and college GPA? MVA

Artificial Neural Network (ANN)

Actual neuron

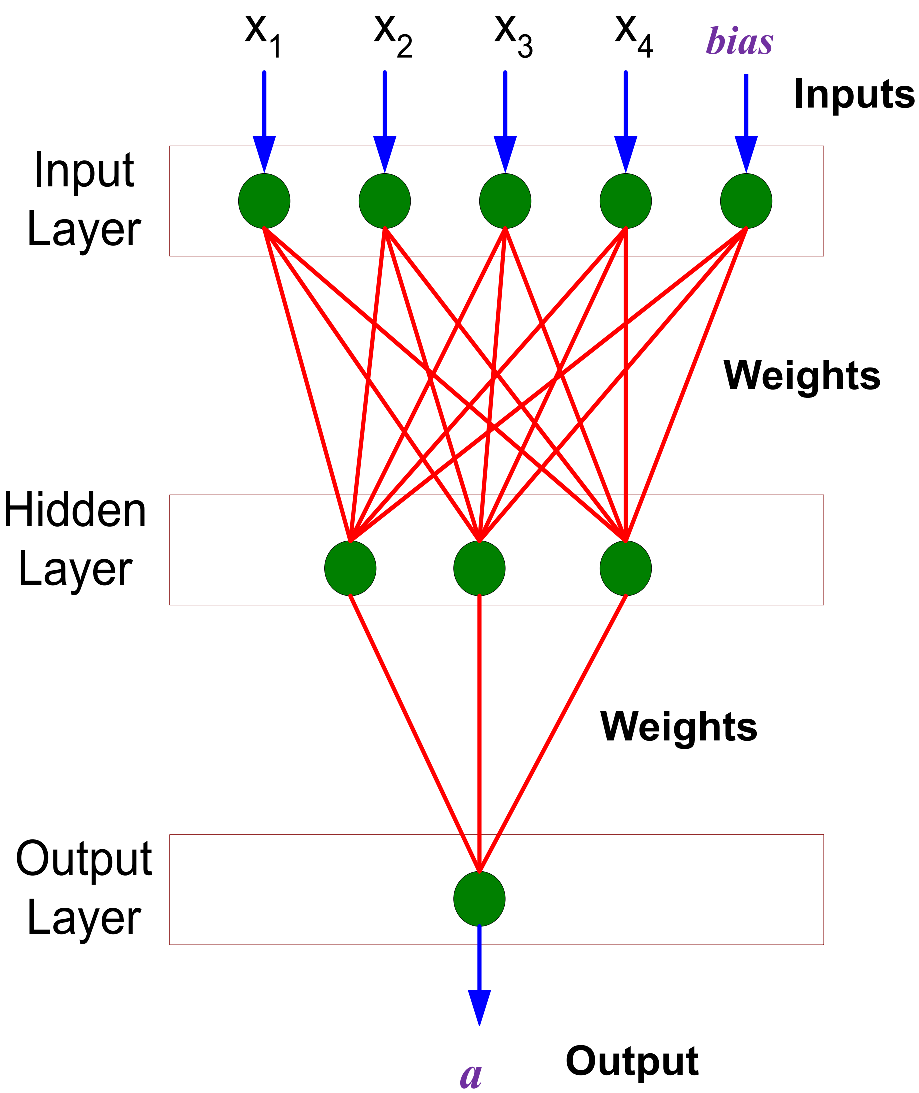


Artificial neuron



- **Artificial neuron** consists of
  - **Input** signals in a vector, **X** from environment (or other neurons)
  - **Weights** in a vector, **W** that are connection strengths
  - **Activation** function, **f(net)** determines the neuron's output based on the **net** = $\Sigma w_i x_i$ and a thresh hold value θ.
- Artificial neuron is the basis for a Artificial Neural Network (ANN)
  - Can be used for machine learning as well as multivariate analysis

Muti-layer Neural Networks with Backpropagation



- **Goal**: Given training data, **find** a set of **weights** that fit outputs of neural net to desired outputs.
- **Mechanism**:
  - For each training example, feed forward for activation.
  - Backpropagate the error to previous layers and adjust the weights slowly in direction that reduces error.
  - Repeat this process until converged and return *f(X, β)*.
- **Applications**:
  Solved many complex real-world problems.

Example: ANN

x_1	x_2	Output
1.0	1.0	1
9.4	6.4	–1
2.5	2.1	1
8.0	7.7	–1
0.5	2.2	1
7.9	8.4	–1
7.0	7.0	–1
2.8	0.8	1
1.2	3.0	1
7.8	6.1	–1

*The weight vector converged after repeated training on the data set, about 500 iterations:

W^{500} = [-1.3, -1.1, 10.9]

f(net) = $w_1x_1 + w_2x_2 + w_3$, where two discriminant functions $\mathbf{g_i}$ and $\mathbf{g_j}$ are the same (border), $g_i = g_j$

f(net) = $\boldsymbol{-1.3x_1 + -1.1x_2 + 10.9}$

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Data Base Development

Copy of Wobbe Index database (1) - Excel

FILE HOME INSERT PAGE LAYOUT FORMULAS DATA REVIEW VIEW

A22 | 19

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1				Blend				Gas		Inert		Thermal			Mole	Specific	Sound	Wobbe	Methane
2	dB	Temp	Pressu	%				%				Conduct	Cp	Cv	Density	Gravity	Velocity	Index	Index
3	#	C	PSI	Fossil	Anerobic	Landfill		CH4	C2H6	CO2		W/(m.K)	J/(mol.K)	J/(mol.K)	L/mol	Kg/(m^3)	m/s	MJ/Nm3	MI
4	1	-20	500	100	0	0		94	6.00	0		0.0274	35.13	26.82	13.50	0.5828	350.86	54.90	84.5
5	2	-20	500	90	10	0		91.83	5.40	2.77		0.0270	35.07	26.76	14.05	0.6066	343.90	52.16	88.8
6	3	-20	500	80	20	0		89.66	4.80	5.54		0.0267	35.01	26.70	14.68	0.6305	336.48	49.53	93.2
7	4	-20	500	70	30	0		87.49	4.20	8.31		0.0263	34.95	26.64	15.24	0.6543	330.29	47.03	97.6
8	5	-20	500	60	40	0		85.32	3.60	11.08		0.0260	34.90	26.58	15.79	0.6782	324.43	44.62	102.0
9	6	-20	500	50	50	0		83.15	3.00	13.85		0.0256	34.84	26.52	16.35	0.7020	318.88	42.32	106.4
10	7	-20	500	40	60	0		80.98	2.40	16.62		0.0253	34.78	26.46	16.90	0.7258	313.60	40.10	110.7
11	8	-20	500	30	70	0		78.81	1.80	19.39		0.0250	34.72	26.40	17.55	0.7497	307.78	37.97	115.0
12	9	-20	500	20	80	0		76.64	1.20	22.16		0.0246	34.66	26.34	18.10	0.7735	303.00	35.91	119.2
13	10	-20	500	10	90	0		74.47	0.60	24.93		0.0243	34.60	26.28	18.66	0.7974	298.44	33.92	123.3
14	11	-20	500	0	100	0		72.3	0.00	27.7		0.0239	34.54	26.23	19.22	0.8212	294.08	32.00	127.3
15	12	-20	500	0	90	10		71.52	0.00	28.48		0.0238	34.54	26.23	19.40	0.8287	292.74	31.51	128.1
16	13	-20	500	10	80	10		73.69	0.60	25.71		0.0241	34.60	26.29	18.84	0.8049	297.04	33.41	124.2
17	14	-20	500	0	80	20		70.74	0.00	29.26		0.0237	34.55	26.24	19.57	0.8363	291.42	31.03	129.0
18	15	-20	500	20	70	10		75.86	1.20	22.94		0.0245	34.66	26.35	18.28	0.7811	301.54	35.38	120.1
19	16	-20	500	10	70	20		72.91	0.60	26.49		0.0240	34.61	26.30	19.02	0.8124	295.66	32.91	125.0
20	17	-20	500	0	70	30		69.96	0.00	30.04		0.0236	34.56	26.24	19.75	0.8438	290.11	30.55	129.8
21	18	-20	500	30	60	10		78.03	1.80	20.17		0.0248	34.72	26.41	17.72	0.7572	306.25	37.42	115.9
2110	2107	80	1000	50	0	50		79.25	3.00	17.75		0.0388	38.96	30.64	24.67	0.7397	397.41	38.80	111.2
2111	2108	80	1000	40	0	60		76.3	2.40	21.3		0.0381	38.88	30.57	25.71	0.7710	389.24	36.21	116.4
2112	2109	80	1000	30	0	70		73.35	1.80	24.85		0.0374	38.80	30.49	26.76	0.8024	381.56	33.73	121.4
2113	2110	80	1000	20	0	80		70.4	1.20	28.4		0.0367	38.72	30.41	27.81	0.8338	374.32	31.36	126.4
2114	2111	80	1000	10	0	90		67.45	0.60	31.95		0.0361	38.65	30.33	31.60	0.8651	351.13	29.08	131.2
2115	2112	80	1000	0	0	100		64.5	0.00	35.5		0.0354	38.57	30.26	32.75	0.8965	344.93	26.90	135.8
2116	2113	80	1500	100	0	0		94	6.00	0		0.0422	39.34	31.03	26.82	0.5828	466.77	54.10	84.5
2117	2114	80	1500	90	10	0		91.83	5.40	2.77		0.0417	39.26	30.94	27.92	0.6066	457.51	51.30	88.8

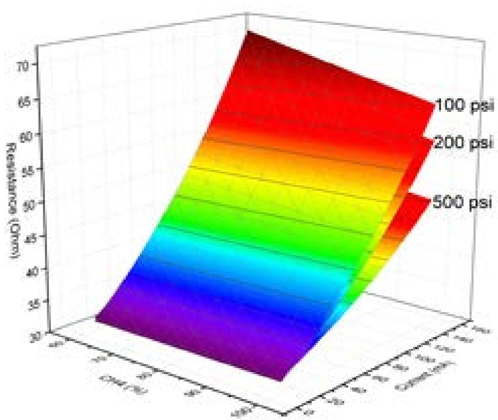
Wobbe Index database

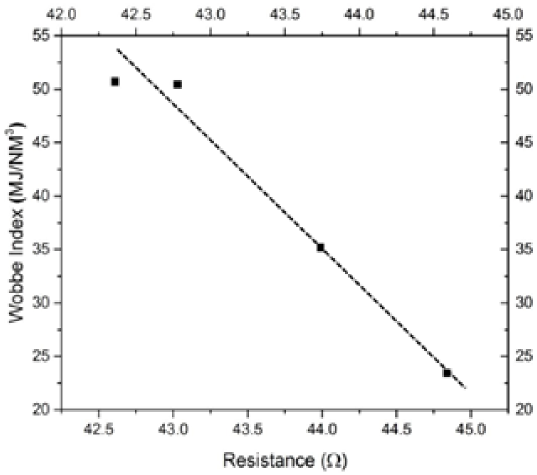
READY AVERAGE: 72.66168955 COUNT: 18 SUM: 1235.248722 100%

- 3 different NG
  1. Fossil
  2. Anerobic
  3. Landfill
- TC, Sound Velocity, Cp and Cv by CHEMKIN transport model
- Wobbe Index by ASPEN equilibrium model
- Methane Index by H/C ratio and SAE 922359 Eqn. 4
- Variable T and P

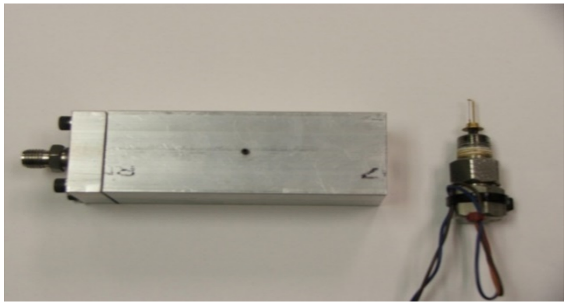
Completion of UCRs Wobbe Index Sensor: 2015

- **Multiple Regression Analysis (Past)**





Developed the function estimating Wobbe Index @5% error



- **Multi-Variate Analysis with ANN**

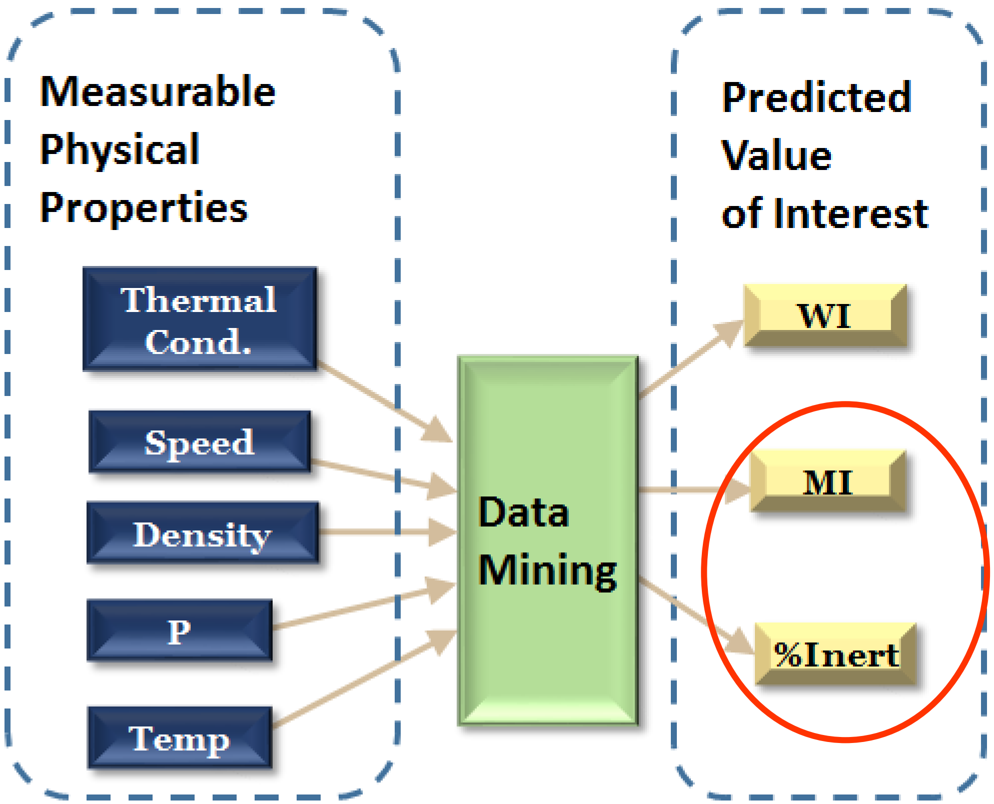
1. Wobbe Index, estimation function was developed for 7 variable.
2. Square some of error for 2346 sample point is 2460. ~1 per sample (~2% error)
3. Reducing the variable to 4 is ongoing

Current Progress

New Sensor Development Approach

- **Plan**
  - Upgrade the NG Sensor for Methane Index
  - Add Speed of Sound Measurement
  - Enhance data analysis
  - Expand test matrix and variable for vehicle use
- **Evaluate**
  - Integrate sensor in a test laboratory for daily usage
  - Integrate sensor in an engine and demonstrate benefit
  - Work planned with Cummins Inc.

Predictive Sensor by Data Mining



Area of interest

Measurable Physical Properties: Speed of Sound

Sound Speed in Gases

The speed of sound in an ideal gas is given by the relationship

$$v_{sound} = \sqrt{\frac{\gamma R T}{M}}$$

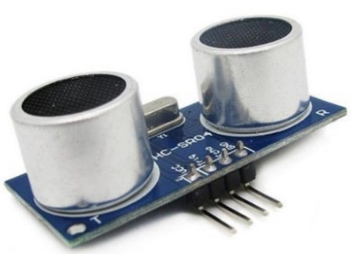
where
γ = adiabatic constant
R = gas constant
M = molecular mass of gas
T = absolute temperature

Show

- R = the universal gas constant = 8.314 J/mol K,
- T = the absolute temperature
- M = the molecular weight of the gas in kg/mol
- γ = the adiabatic constant, characteristic of the specific gas

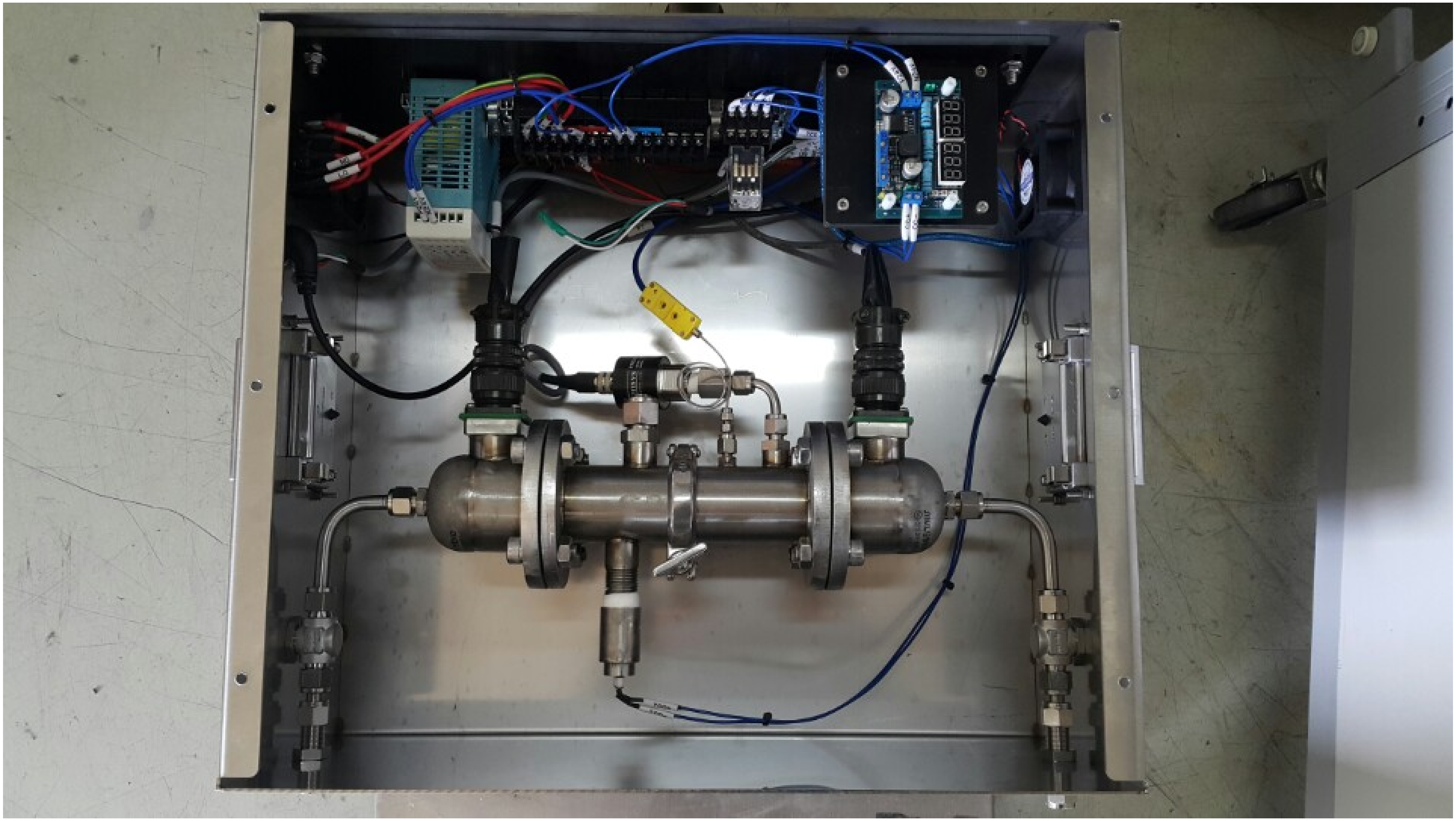
$$\gamma = \frac{C_P}{C_V}$$

Ar, He = 1.6
N_2, O_2, H_2 = 1.4
CO_2 = 1.29
CH_4 = 1.32
C_2H_6 = 1.22
C_3H_8 = 1.12



HC-SR04 Ultrasonic Range Finder

Current Progress: Sensor Layout



Sensor Data Build Gas Matrix

Description	Methane (mole %)	Ethane (mole %)	Propane (mole %)	I-butane (mole %)	CO_2 (mole %)	MN
Rocky Mountain pipeline	94.5	3.5	0.6	0.3	0.75	93.58
Peruvian LNG	88.3	10.5	0	0	0	84.11
Associated High Ethane	83.65	10.75	2.7	0.2	0	74.51
Associated High Propane	87.2	4.5	4.4	1.2	0	74.31
Low MN Gas	82.8	4.5	8.8	1.2	0	65.07
Methane	100	0	0	0	0	107.62

Sensor Data Build Properties Matrix

Temp (° C)	Pres (bar)	Gas composition (pure and arbitrary mix)						Gas properties		Wobbe Index (MJ/m^3)	Methane Number
		1	2	3	4	…	….	Therm Cond. (W/(m.K))	Sound velocity (m/s)		
0	1										
10	2										
20	3										
30	4										
40	1										
50	2										

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