APPLICATION OF MACHINE LEARNING ALGORITHMS TO ON-BOARD DIAGNOSTICS (OBD II) THRESHOLD DETERMINATION

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MATHWORKS AUTOMOTIVE CONFERENCE 2017

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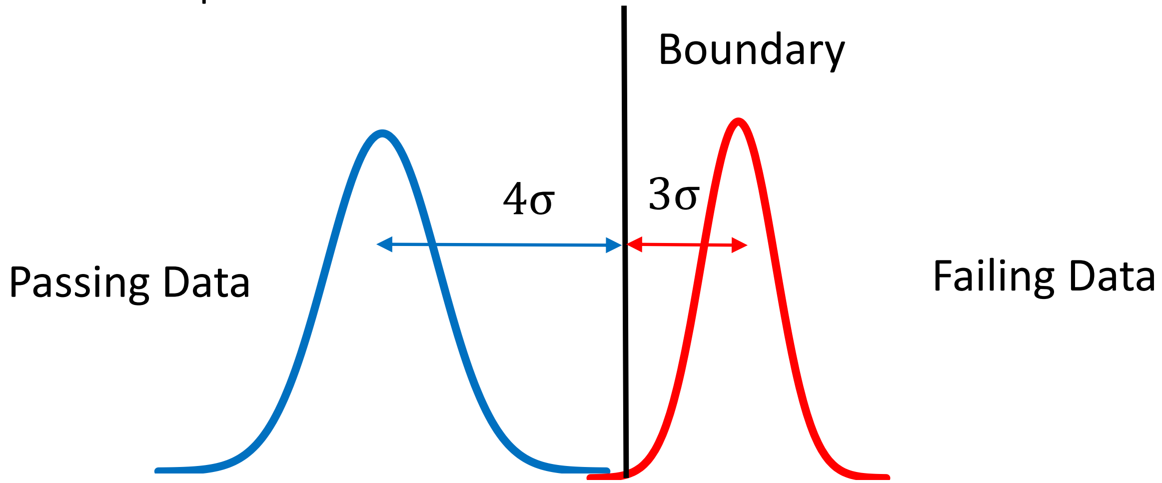
Machine Learning for OBD

Background: On-Board Diagnostics & Boundary

- On-Board Diagnostics is the requirement that vehicles must light the Malfunction Indicator Light (MIL) if an emissions related component is reporting a signal outside its expected operating range
  - A threshold is determined based on empirical data
    - 4σ/ 3σ: Preferred Guideline
    - More separation is better



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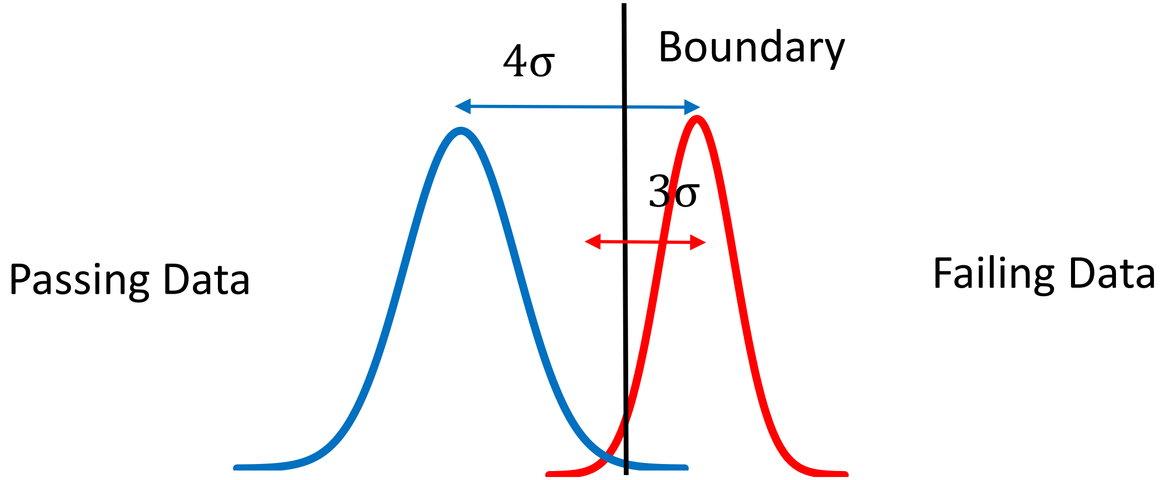
Background: On-Board Diagnostics & Boundary

- Separation is needed to minimize:
  - False failure
  - False pass
- Diagnostic should run consistently on
  - The certification test cycle: FTP75
  - In the field: In Use Monitoring Performance Ratio (IUMPR)



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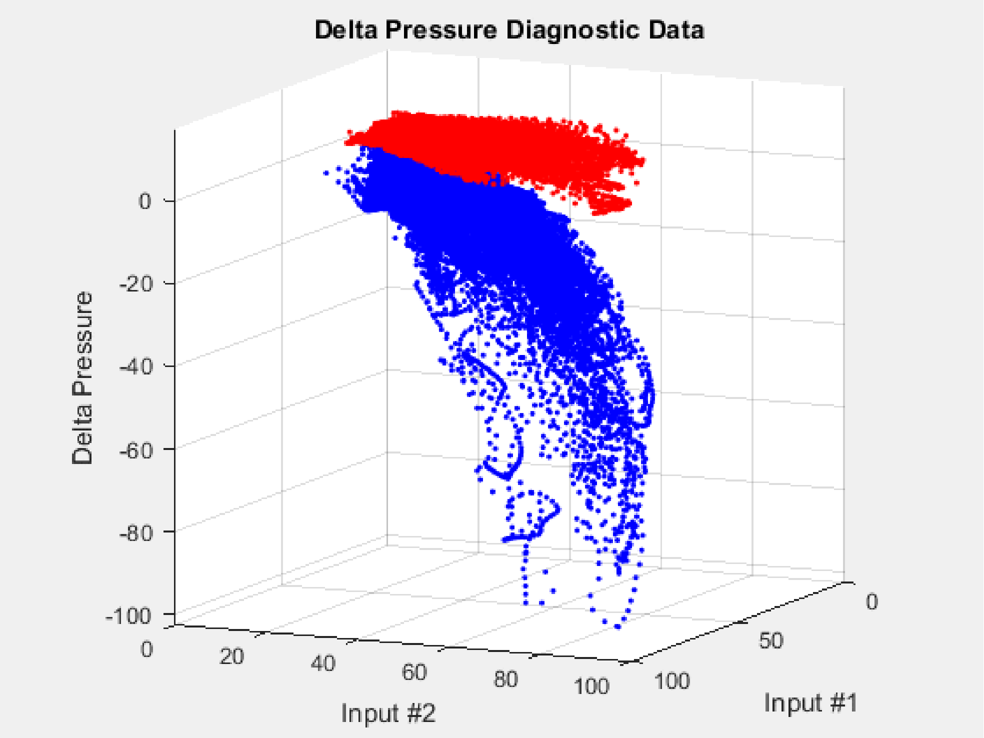
Example: Pressure Sensor Diagnostic



- OBD Goal:
  - Monitor pressure and determine whether connection is connected or disconnected
  - Delta pressure sensor (dP) measures pressure relative to atmosphere
    - Disconnected/Failing – positive pressure
    - Connected/Passing – negative pressure
  - All data units are normalized
  - Select the range (enable criteria) where separation is acceptable
    - Use values of Input #1 and Input #2 where there is no overlap
  - Determine the separation boundary
    - dP above the boundary – Light the MIL !!!

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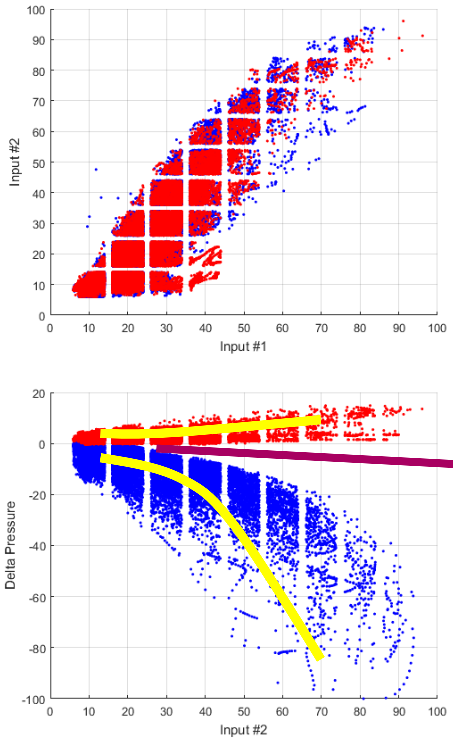
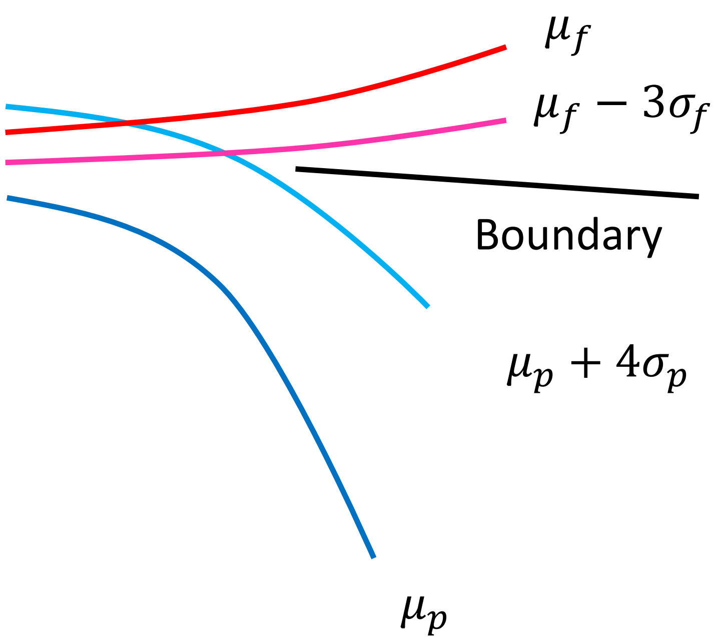
OBD Boundary Determination: Classic Method





- Make a grid of Input #1 & #2
- Each set of grid points has a column of passing & failing data
- Within each of the columns calculate for dP:
  - Mean (passing, failing) μ_p, μ_f
  - Standard Deviation (passing, failing) σ_p, σ_f
- Compute acceptable boundaries:
  - Failing: $\mu_f - 3\sigma_f$
  - Passing: $\mu_p + 4\sigma_p$
- Separation is achieved where
  - $\mu_p + 4\sigma_p < \mu_f - 3\sigma_f$

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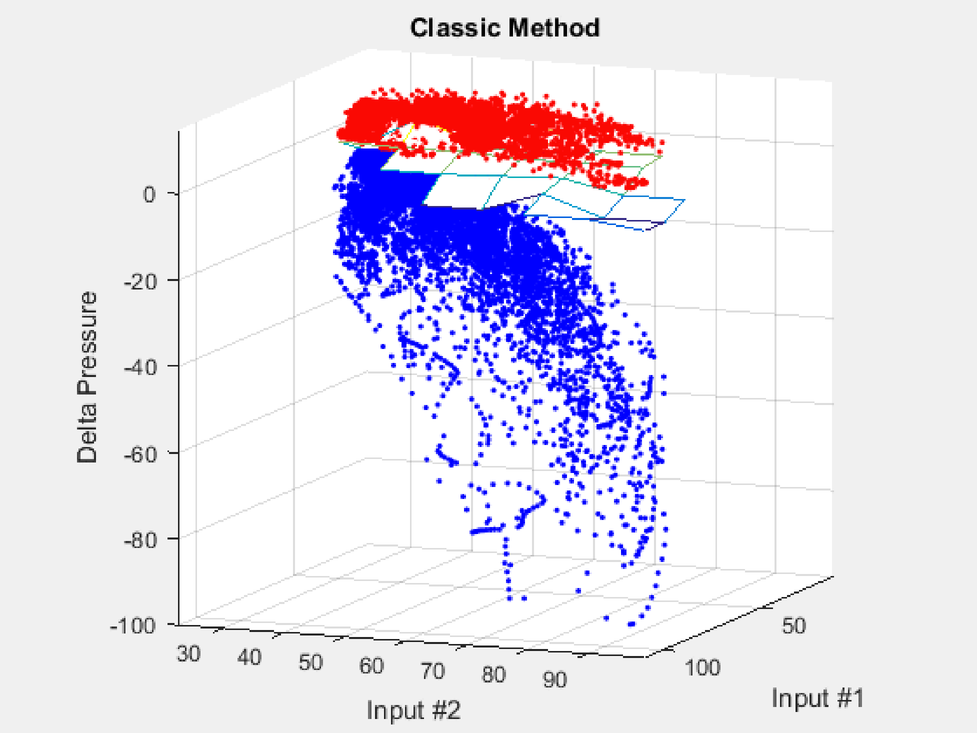
OBD Boundary Determination: Classic Method



- Adjust the enable criteria to:
  - Enable the monitor at any coordinates where separation is achieved
  - Where separation is marginal, enable the monitor by selectively adding coordinates until monitor runs frequently enough to meet in use monitor criteria
- Calculate the boundary based on the larger of:
  - $\mu_p + 4\sigma_p \, , \mu_f - 3\sigma_f$

Use statistical analysis to guide us before we put the enable criteria and boundary in the controller!

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Machine Learning for OBD
Rationale for Machine Learning

- Data is continuous and plentiful
  - Fit a continuous function

- What is Machine Learning?
  - The ability of computers to learn without explicitly being programmed
  - Inputs predict the outputs via a model which has been fit
  - Fitting is known as training or optimization
    - Multiple Linear Regression
    - Logistic Regression
    - Multivariate Gaussian Distribution
    - Principle Component Analysis

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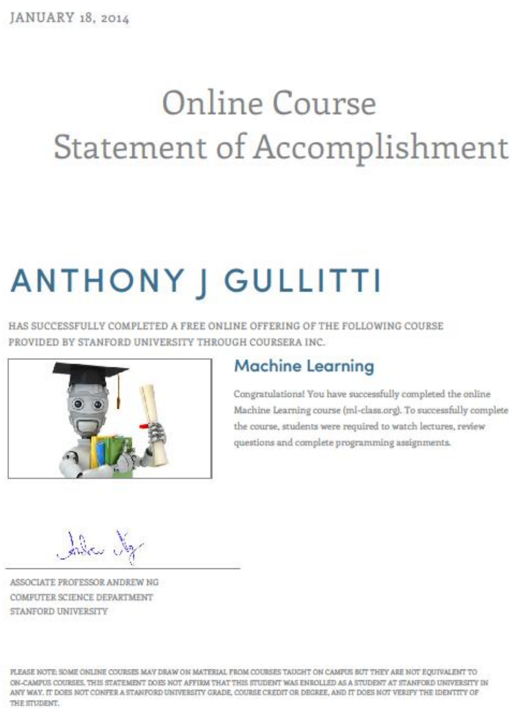
Machine Learning for OBD

Freely Available: Coursera Machine Learning Course



JANUARY 18, 2014

Online Course
Statement of Accomplishment

ANTHONY J GULLITTI

HAS SUCCESSFULLY COMPLETED A FREE ONLINE OFFERING OF THE FOLLOWING COURSE PROVIDED BY STANFORD UNIVERSITY THROUGH COURSERA INC.

Machine Learning

Congratulations! You have successfully completed the online Machine Learning course (ml-class.org). To successfully complete the course, students were required to watch lectures, review questions and complete programming assignments.

ASSOCIATE PROFESSOR ANDREW NG
COMPUTER SCIENCE DEPARTMENT
STANFORD UNIVERSITY

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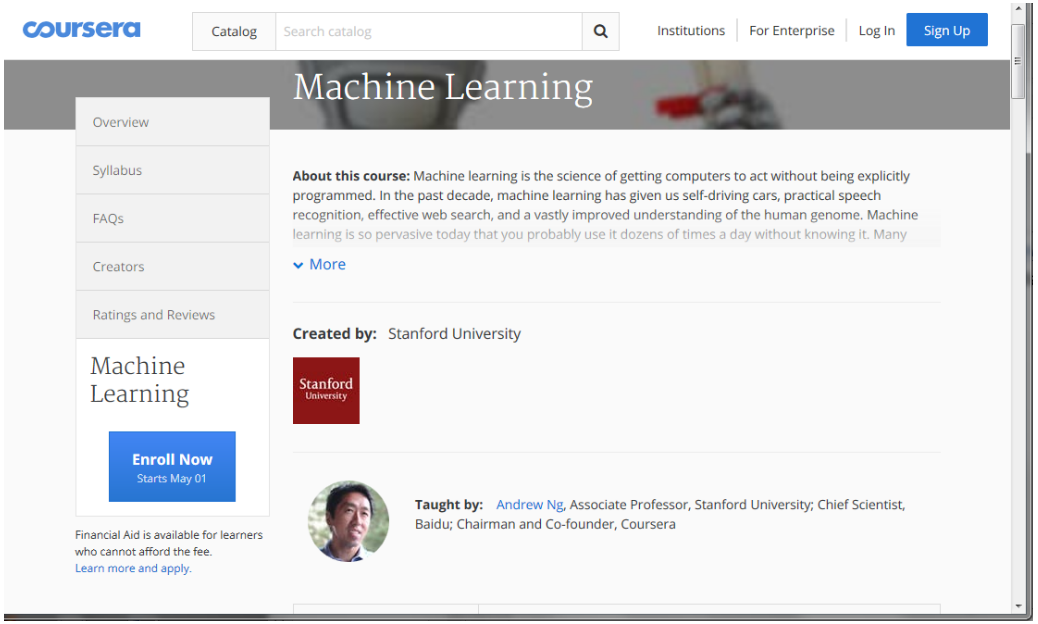
Machine Learning Course, Andrew Ng



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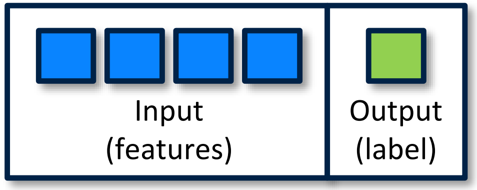
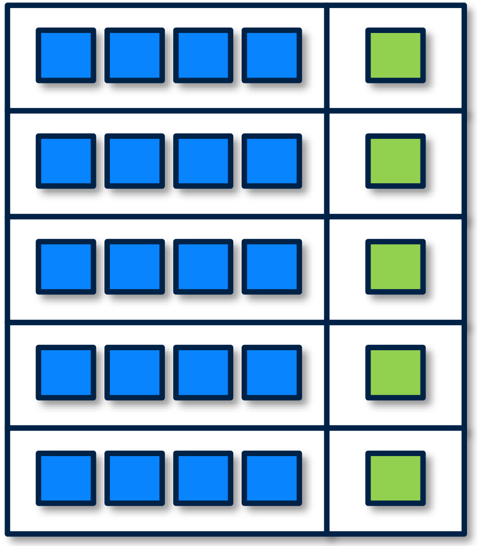
Supervised Machine Learning

New Dataset

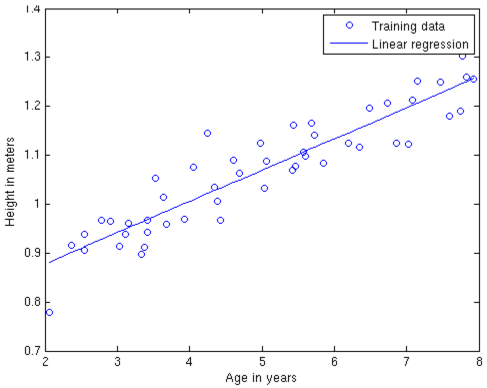


Training Dataset Population



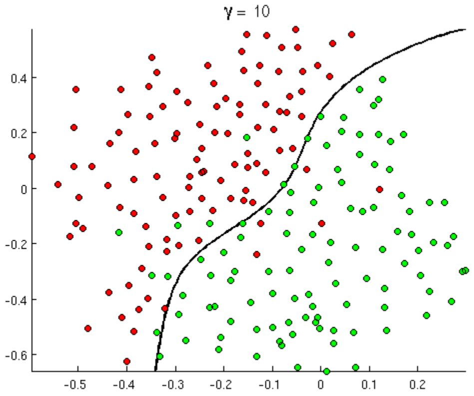
Two Types:

Regression



Output has continuous possible range

Classification



Output has a ***discrete*** possible range

Given the input feature set, ***predict*** *the most likely output label value.*

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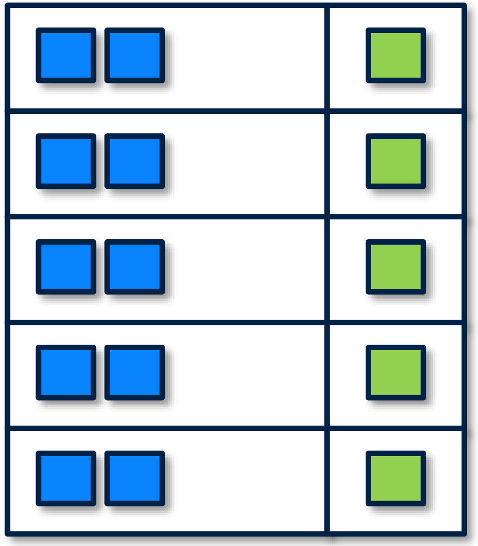
Regression

Training Dataset
Population

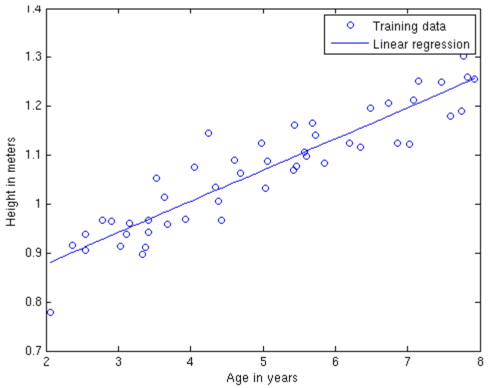


$$y_p(x_1,x_2) = f\left(\begin{matrix}\theta_0 + \theta_1 x_1 + \theta_2 x_2 + \theta_3 x_1 x_2 + \cdots \\ +\theta_4 x_1^2 + \theta_5 x_2^2\end{matrix}\right)$$

$$y_f(x_1,x_2) = f\left(\begin{matrix}\theta_0 + \theta_1 x_1 + \theta_2 x_2 + \theta_3 x_1 x_2 + \cdots \\ +\theta_4 x_1^2 + \theta_5 x_2^2\end{matrix}\right)$$

- Where:
  - x_1 = Input #1
  - x_2 = Input #2
  - $y_p(x_1,x_2)$ = Delta Pres Passing data
  - $y_f(x_1,x_2)$ = Delta Pres Failing data
- [b,bint,r,rint,stats] = **regress**(y,X,alpha);
  - **alpha** is the requested confidence interval to be returned in **bint**

Regression



Output has continuous possible range

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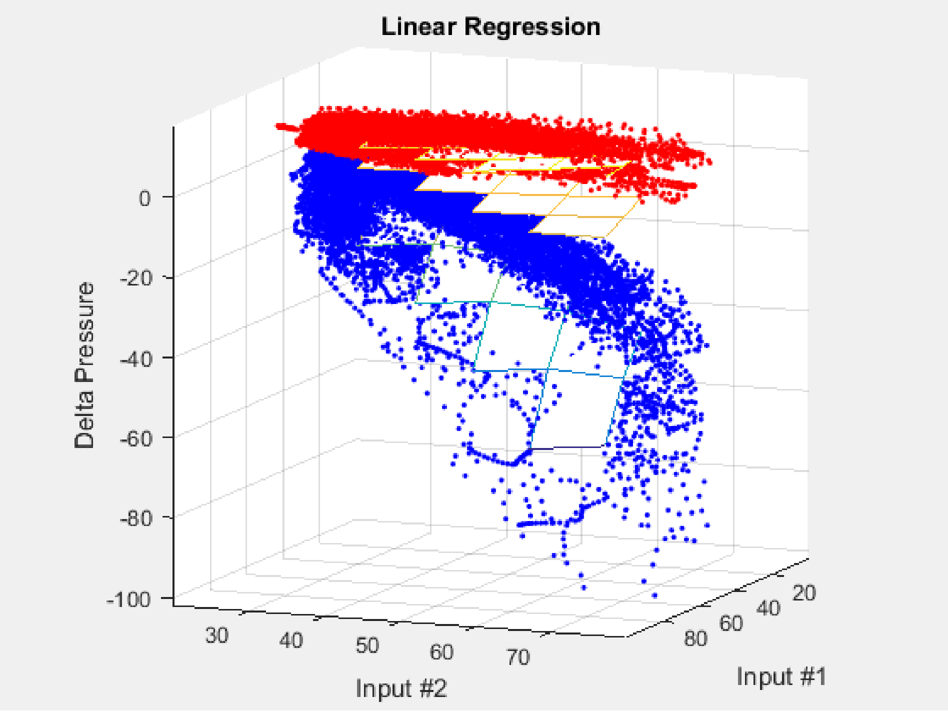
Machine Learning for OBD
Multiple Linear Regression



- Determine the parameters, $y(x_1,x_2)$: θ such that:
  - $y(x_1,x_2)$ predicts the mean value of dP
  - Confidence interval of fit determines separation
    - -3σ = 99.557% Confidence interval failing
    - 4σ = 99.987% Confidence interval passing
- Adjust the threshold as before
- Give the algorithm some help
  - Filter out passing & failing data that overlap

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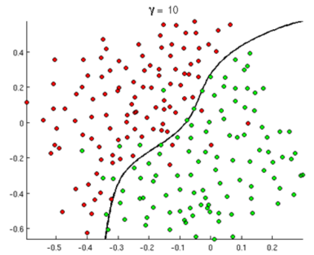
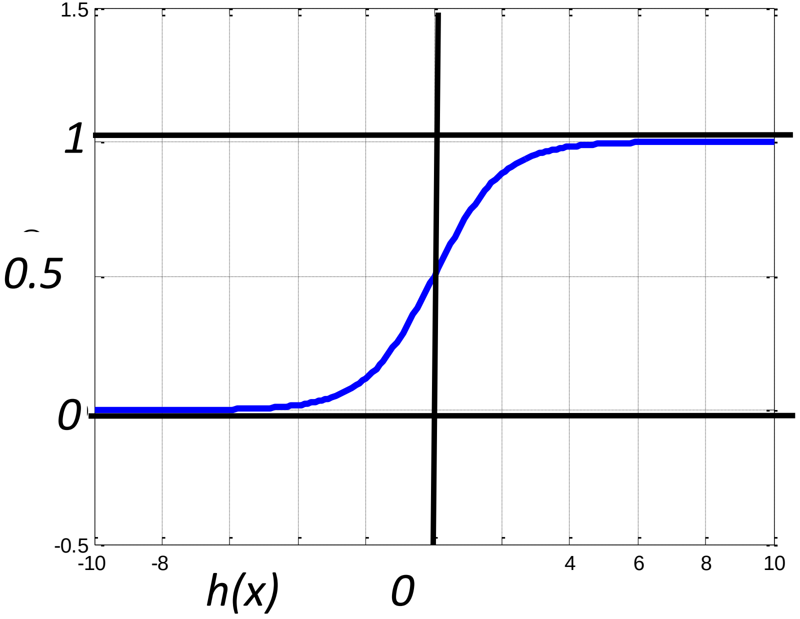
Logistic Regression: A Classification Approach



- Define an equation to be used as the boundary
  - $h(x) = \theta_0 + \theta_1 x_1 + \theta_2 x_2 + \theta_3 x_3 + \theta_4 x_1 \; x_2 \; x_3 + \cdots + \theta_5 x_1^2 + \theta_6 x_2^2 + \theta_7 x_3^2$
    - x_1 = Input #1
    - x_2 = Input #2
    - x_3 = dP ← Now an input!
- Predict the ***probability*** that signal is passing
- The probability is achieved by using the ***sigmoid*** function

$$sigmoid(h(x)) = \frac{1}{1 + e^{-h(x)}}$$

- Find the coordinates of Input #1, Input #2 and dP where:
  - *sigmoid(h(x))* = 0.5
  - The resulting surface is the boundary



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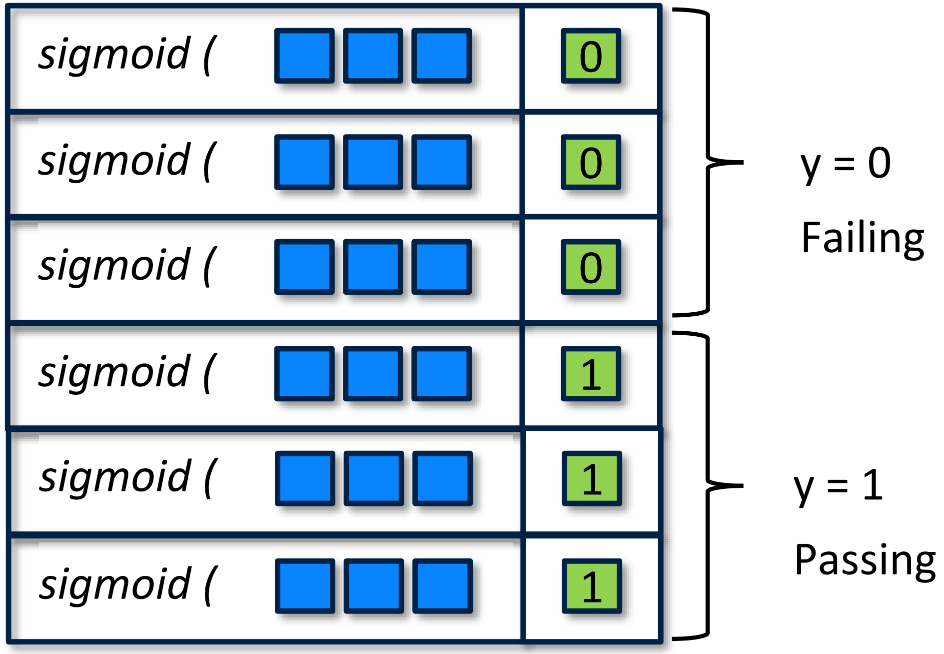
Machine Learning for OBD
Logistic Regression Training

Create *y* such that:



- Optimize the parameters of *h(x)*:*ϑ*
  - *y = sigmoid(h(x))*
  - Minimize the difference between
    - 0 and *sigmoid(h(x))* for failing data
    - 1 and *sigmoid(h(x))* for passing data
- **MATLAB: fminunc** – find the minimum of unconstrained multivariable function
- Objective function (Matlab syntax)

```
J = sum(...
y     .*(log(sigmoid(X*theta))) + ...
(1-y) .*(log(1-sigmoid(X*theta))) ...
 )/(-m) + ...
lambda./(2*m).*sum(theta(2:end).^2);
```

- ***Regularized*** Logistic Regression

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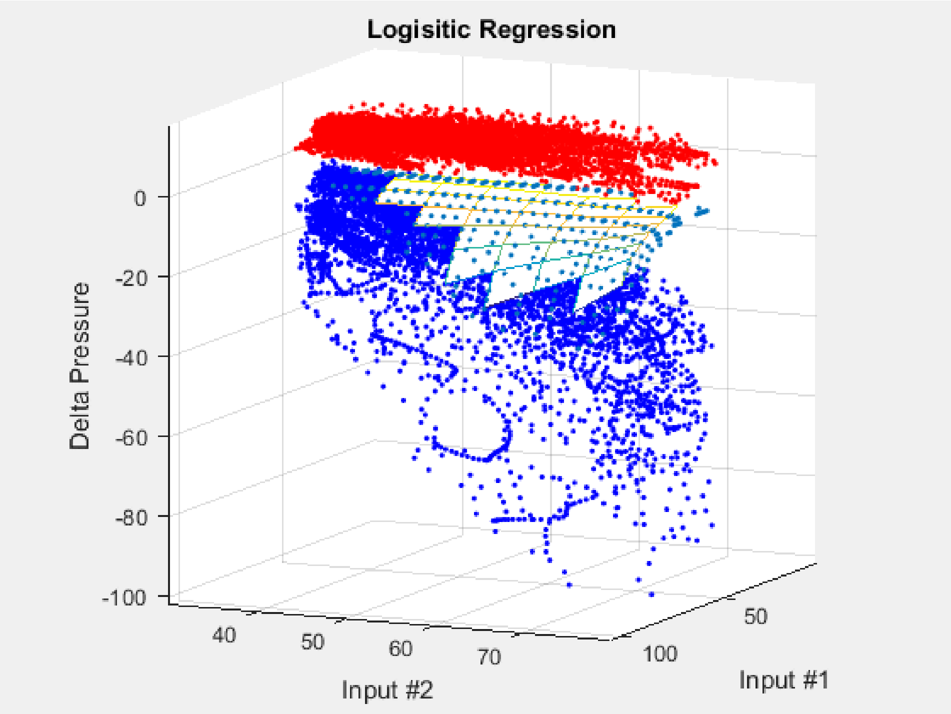
Logistic Regression Boundary



- To obtain the boundary
  - Create a grid of points in the three dimensions – **fullfact**
    - In 2D can use contour plot
  - Input the grid values to the trained equation
    - *sigmoid(h(x))*
  - Find the coordinates where
    - *sigmoid(h(x))* = 0.5
    - Range 0.45 to 0.55
- Explore adjusting the probability value to achieve the desired separation
  - Closer to 1 → passing bias
  - Closer to 0 → failing bias

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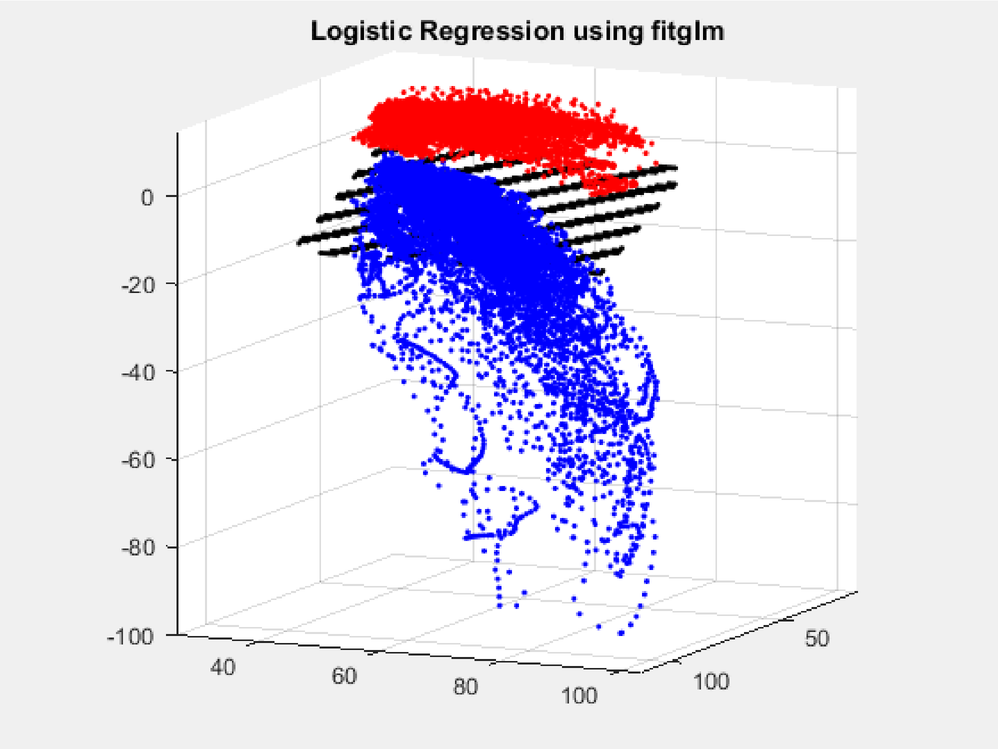
Logistic Regression Using Matlab Command Line



- Logistic Regression using Matlab routines
  - Script/Command line interface

mdl = **fitglm**(X,y,'Distribution','binomial','Link','logit');

Xnew = grid of points

P = **predict**(mdl, Xnew);

ythres = P > 0.45 & P < 0.55;

Xnew(ythres) → boundary

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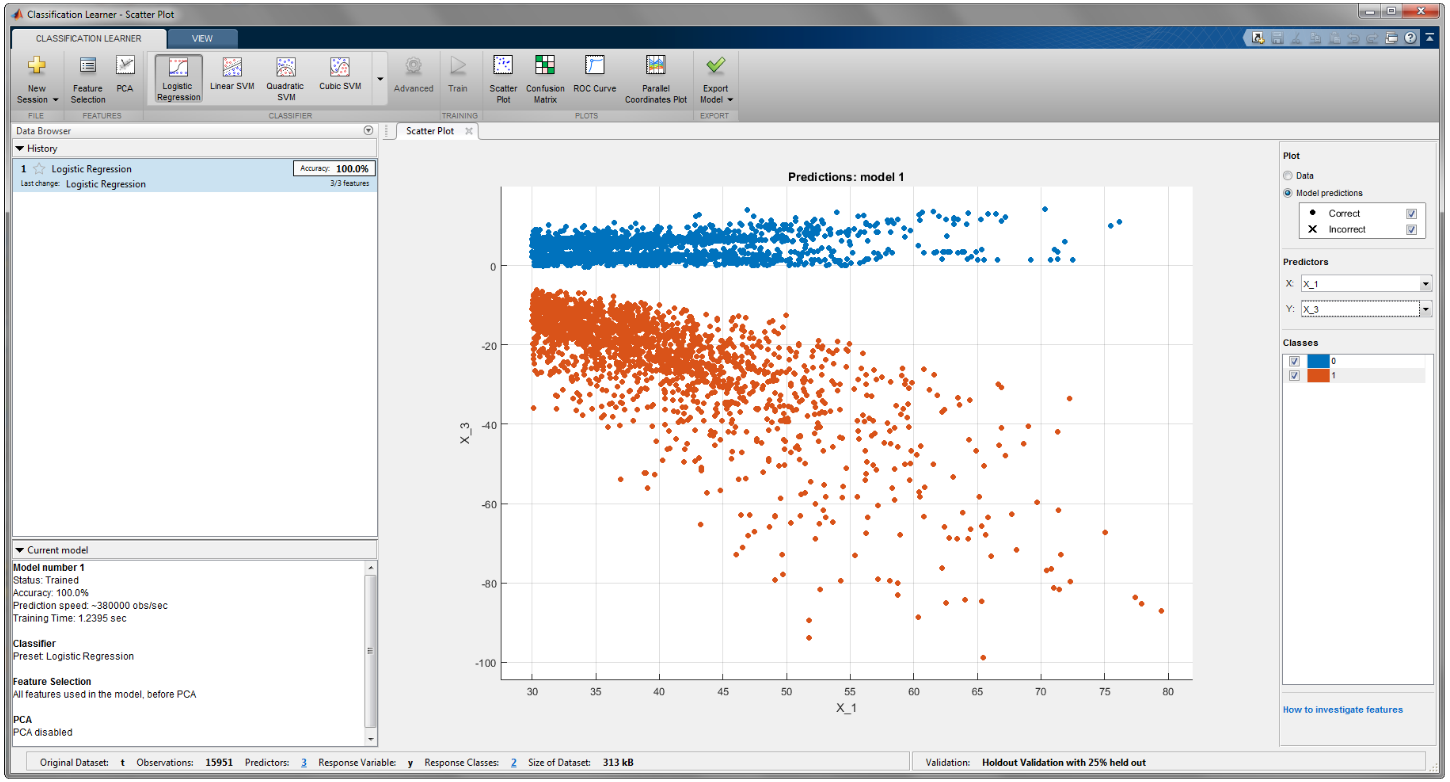
Logistic Regression Using Matlab Classification Learner App



- Classification Learner App
  - T = **table**(X,y);
  - Logistic Regression & more!
  - Extract to the model to the workspace

mdl = trainedModel.GeneralizedLinearModel;

Xnew = grid of points

P = predict(mdl, Xnew)

ythres = P > 0.45 & P < 0.55;

Xnew(ythres) → boundary

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Machine Learning for OBD
Further Approaches

- Multivariate Gaussian Distribution
- Principal Component Analysis

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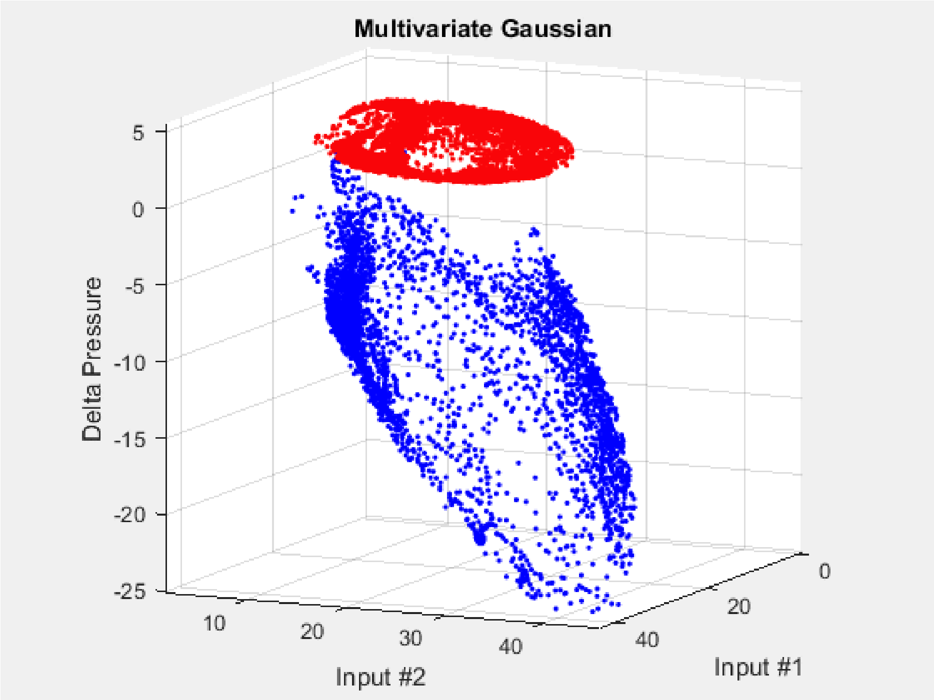
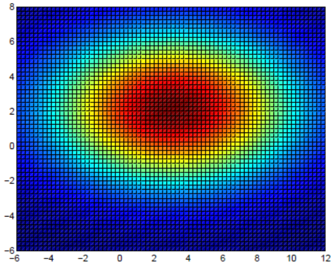
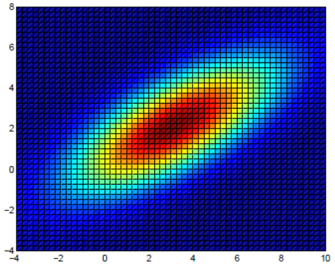
Multivariate Gaussian Distribution

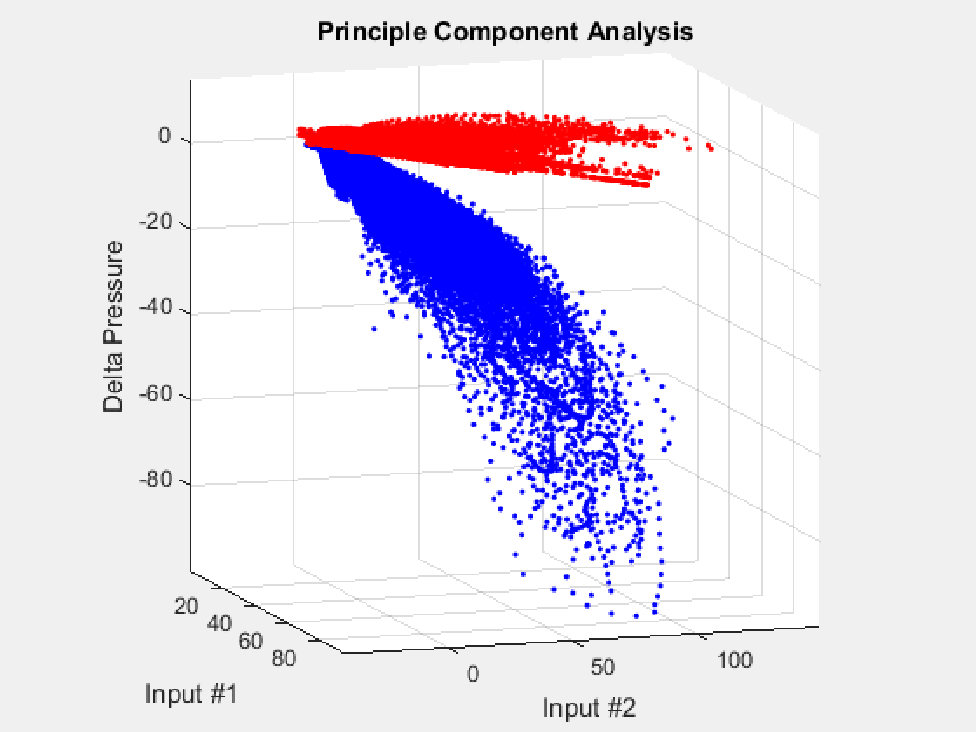






- Model data using Multivariate Gaussian Distribution
- Shown: 2σ of passing/failing
- Better applied to anomaly detection
  - Only passing data
  - Find outliers

Machine Learning for OBD
Principal Component Analysis



- Principal Component Analysis Method
  - Reduce the dimensions from 3D to 2D
  - Boundary could be a curve instead of a surface
- Can be used for higher dimensional data
  - Handling of a monitor with 4+ inputs
    - Reduce to 3D or 2D

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Summary

- On-Board Diagnostics boundaries can be calculated using statistical techniques
  - Widely used - classic method using a grid of points
- Classic OBD boundary setting reduces the data to a grid of points as a basis for the boundary
- Machine learning introduces the concept of using continuous functions as a basis for the boundary
  - Regression: Linear Regression use confidence interval for 4σ/ 3σ separation
  - Classification: Logistic Regression provides a direct method for determining the boundary
- Striving for: Better quality boundaries, obtained more quickly, using less data
- OBD boundary determination is emerging as an excellent application for machine learning !

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THANK YOU

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Machine Learning for OBD
PS

Youtube “big bang theory check engine light”

https://www.youtube.com/watch?v=KMhp2ShPVQw