CO3511
Fuzzy Logic
Assignment Report

Contents

Abstract

This paper serves a brief overview of the programmed Fuzzy Logic Assignment work **FuzzyEngine.** Furthermore, it gives an insight of all relevant tools and libraries used, as well as the program implementation and fuzzy implementation and calculations. Finally it evaluates possible improvements and describes the author's conclusion.

Introduction

Today, simulation games, especially racing simulations, are getting more and more realistic.

In the past, racing simulations represented engine sounds by simply pitch shifting a generic sound sample of an engine. The realism provided by this technique was very poor.

In current racing simulations, sound engineers try to create the perfect engine sound representation. This is often related to recording car engines at different speeds (RPM – Rounds per Minute) and under different loads. Generally, at least 7 samples have to be recorded from a real car (determined by analysing folder structure of typical racing games):

- Idle
- Low rpm – high load
- Mid rpm – high load
- High rpm – high load
- Low rpm – low load
- Mid rpm – low load
- High rpm – low load

After that, the game engine has to loop these samples, pitch shift them and adjust their volumes according to given values (rpm and load). To provide the best sound experience, engineers calculate volume and sample-fading with complicated mathematical models (Sonory.org / Smith).

The approach for this project was to simplify realistic sound representation by using Fuzzy operations instead. Furthermore, to simulate a running engine, Fuzzy operations have been used to calculate the load (vector) and behaviour of a typical combustion engine.

Problem

Many developers use a form of sound synthesis (source) to achieve realistic sound.
Unfortunately it is very hard to find information on techniques used in the top racing simulations.
It seems like the sound engineers and developers don't want to share their experience, leading to confusion and a sort of black-box sound engine, which takes values and returns appropriate sound.

Sonory (Sonory SESP), for example takes a similar approach, stating, that for real life simulation 2 values are needed to calculate proper engine sound output: engine speed (rpm) and load (power).
To connect these values to a real engine, Sonory installs an optical sensor directed to the belt pulley to obtain engine rpm (figure 1). Furthermore to obtain the current engine load, a pressure sensor is connected to the intake manifold tubing, determining the engine load by measuring the pressure of air flowing into the engine (figure 2). At the end, they simply connect the audio output of their processor to the car's stereo system.

Figure 1

Figure 2

Sonory demonstrates their engine samples by using software called FMOD Designer. FMOD in turn states that its "the" choice for game sound engineering.

I chose to develop my own solution approach by using Fuzzy Logic methods, inspired by the accurate sound representation in actual racing simulations. Furthermore I wanted to design my software openly, retaining the option to be able to connect real car values if I want to (besides the option of calculating engine rpm thru the fuzzy logic inference set)

Solution approach

The program developed due to this assignment has to fulfil the following tasks in order to simulate engine sound:

- Simulate engine behaviour by calculating rpm increase and decrease load vector with a fuzzy logic system
- Read in single .wav samples, which represent different rpm under different loads
- Loop these samples
- Pitch these samples according to the current rpm
- Adjust single volumes and fade between samples by using fuzzy logic inference systems
- Implement a simple GUI to illustrate function and to demonstrate the audio sample's behaviour

Implementation

Tools

Microsoft Visual Studio 2010

Visual Studio is an integrated development environment by Microsoft, offering different programming languages like Visual Basic, C, C++, C# and F# and therefore covering the whole Microsoft portfolio. Visual Studio allows its programmers to develop classic windows applications or dynamic websites (and web services). It fulfils basic requirements like code highlighting, completion and debugging.

Microsoft Visual studio provides a long list of handy features, making it easy and intuitive to use. Moreover it offers graphical Interfaces to include and configure libraries, databases and many more.

In this assignment approached, Windows Presentation Foundation (WPF) and C# have been used to implement the whole solution. WPF is a graphic framework and a part of Microsoft's .NET framework. In WPF, presentation and coding logic is separated. In the presentation layer, the XML based language XAML defines the GUI hierarchy, its controls and properties. It is very simple to learn and follows a kind of *what you see is what you get* approach. It serves a huge list of interactive controls (such as lists, menus, buttons, calendars, grids) by default and allows to develop either in the XAML code or directly in a GUI builder (Figure 3)

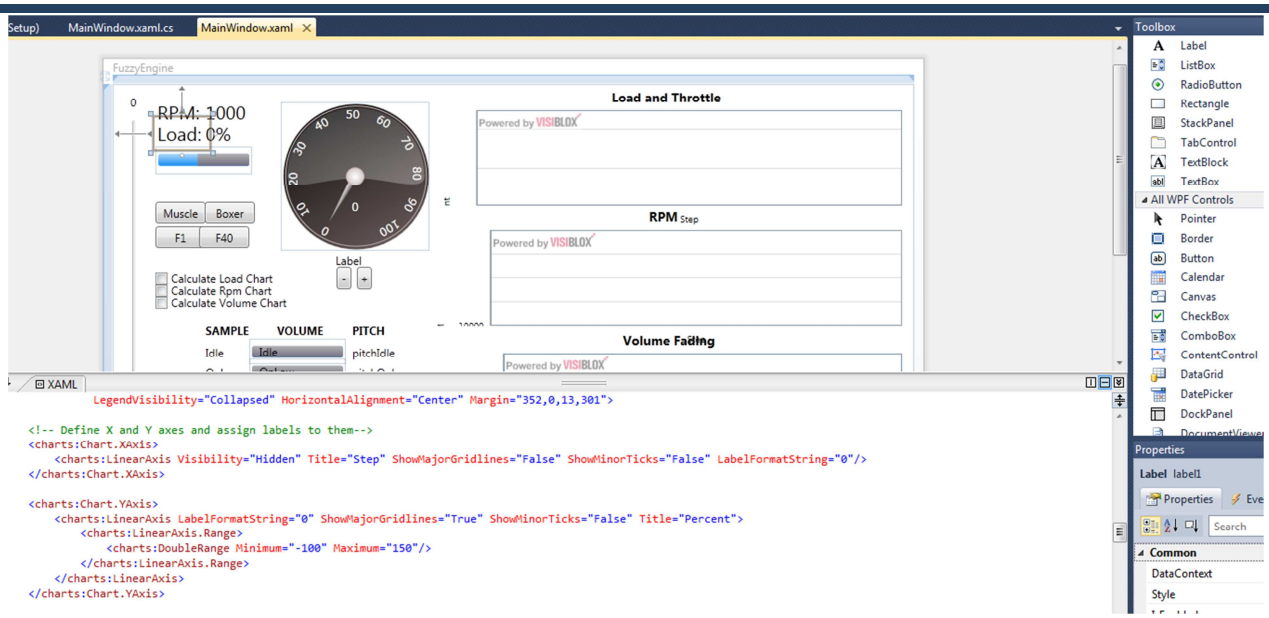


Figure 3

Libraries and frameworks

DotFuzzy library

DotFuzzy is a fuzzy logic library written in C# and therefore useable by all languages, which the .NET environment supports. It is open source and very easy to use.
Basically it works as a FCL (Fuzzy Control Language) parsing and calculating tool, operating with the centroid method (COG). It is freeware and therefore free to use (DotFuzzy).

In this assignment it is used to calculate fuzzy sets on a cyclic basis (every 20ms).

Microsoft XNA framework

Microsoft's XNA (**X**NA's **N**ot **A**cronymed) framework is a game developing technology for Microsoft Windows, Xbox 360, Zune and Windows Phone 7.
It combines different programming interfaces, such as Direct3D XACT and XInput in a common framework. This guarantees a fast Microsoft Windows game development and supply of development tools, which have only been available for Xbox 360 so far (XNA Developer Center).

In this assignment, Microsoft XNA is used for WAV sample playback, pitch shift and volume control. After hourly research of pitch shifting libraries, it seems to be the only accurate and performance-oriented solution in the .NET world.

SlimDX framework

SlimDX is a open source and free framework to allow developers to easy implement DirectX applications using C#, VB.NET and IronPython. It is licensed under the MIT/X11 license (SlimDX).

In this assignment, SlimDX is used to provide joystick input device usability. In this specific case I used the digital/analog input device **HAMA PC-Gamepad *Black-Force*** (Figure 4). The program determines a connected DirectX input device and reacts to its input by letting the user control throttle and up/downshift.

(Figure 4)

Codeplex Dashboarding Library

Codeplex is an open source community offering (among other things) a collection of dashboard gauges for Silverlight 2.0 and Windows Presentation Foundation (Codeplex).

In this assignment, the following Codeplex dashboard controls have been used:

- 360dial (Figure 5)
- ProgressBar (Figure 6)

(Figure 5)

SAMPLE	VOLUME	PITCH
Idle	39,44642	0,419
OnLow	31,92097	0,4514
OnMid	0	-0,1486
OnHigh	0	-0,5486
OffLow	12,12525	-0,5486
OffMid	12,12525	-0,5486
OffHigh	0,8238873	0,2514

(Figure 6)

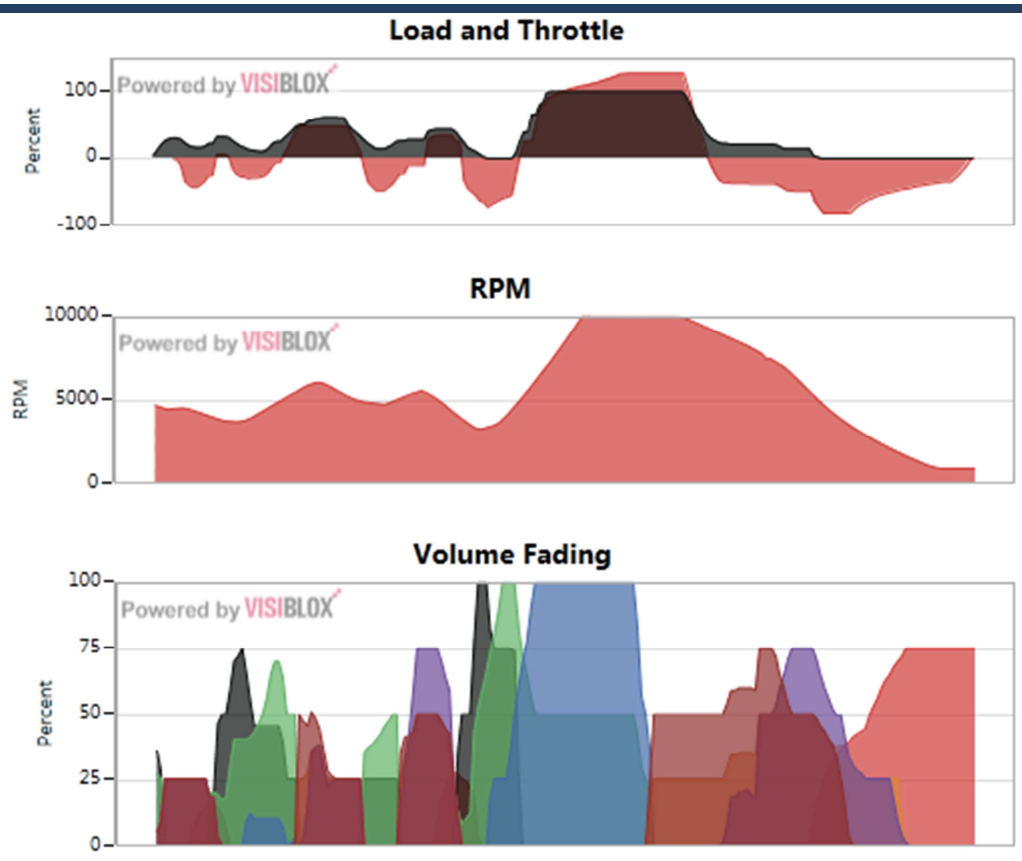
Visiblox charts library

Visiblox Charts serves simple and very high performant charts, which can be customized to fit the developer's needs. The free version is free to be used in production environment and comes with a small watermark (Visiblox).

When researching appropriate charts, I firstly stumbled upon the WPFtoolkit chart controls. Unfortunately WPFtoolkit is not able to perform as wanted, leading the whole application to have very poor performance.

In this assignment Visiblox charts are used to illustrate the following values (Figure 9)

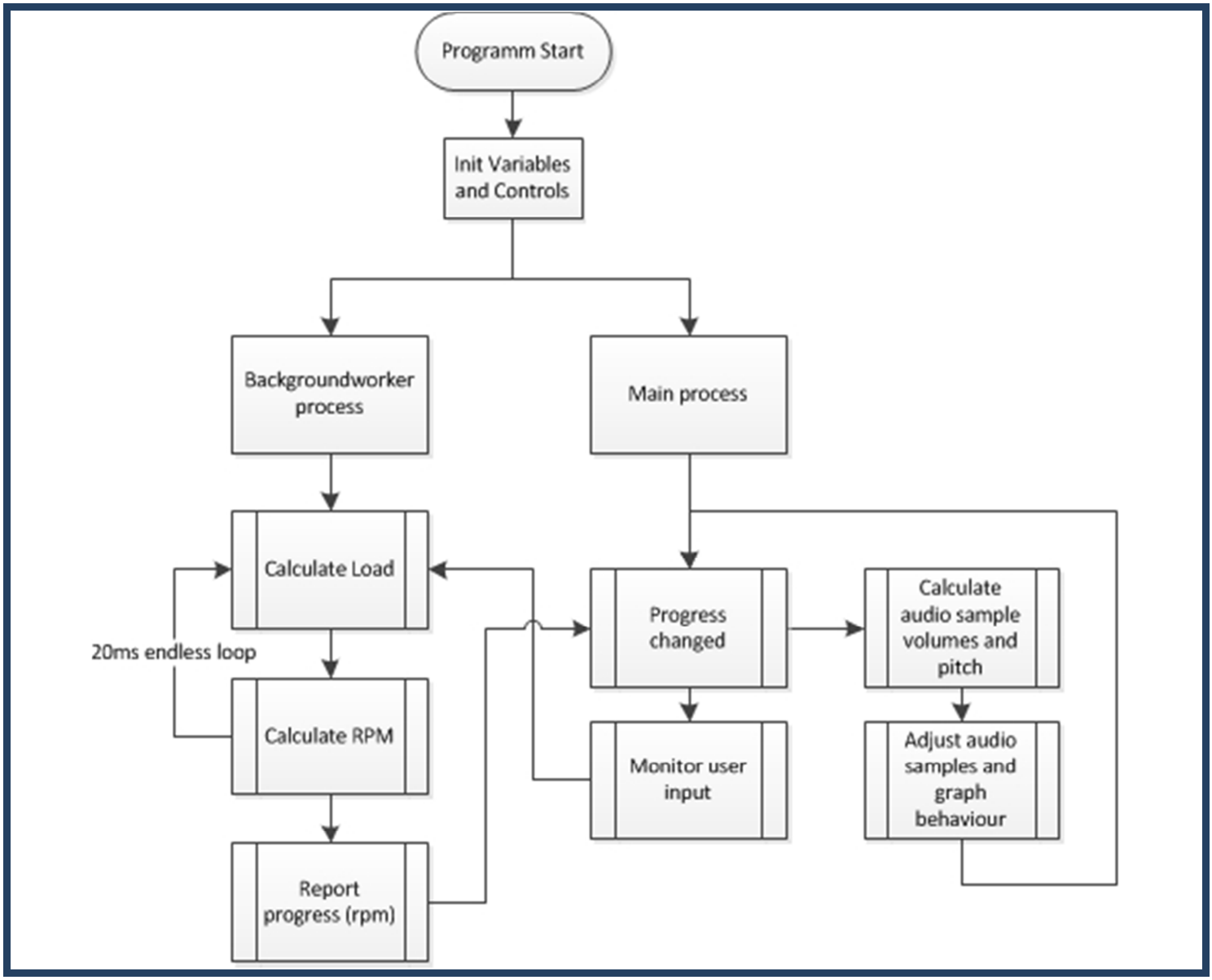
- Throttle (black) and load (red) percentage
- Engine rpm (red)
- Sample volume fading (colors are assignable to the sample volume values next to it)



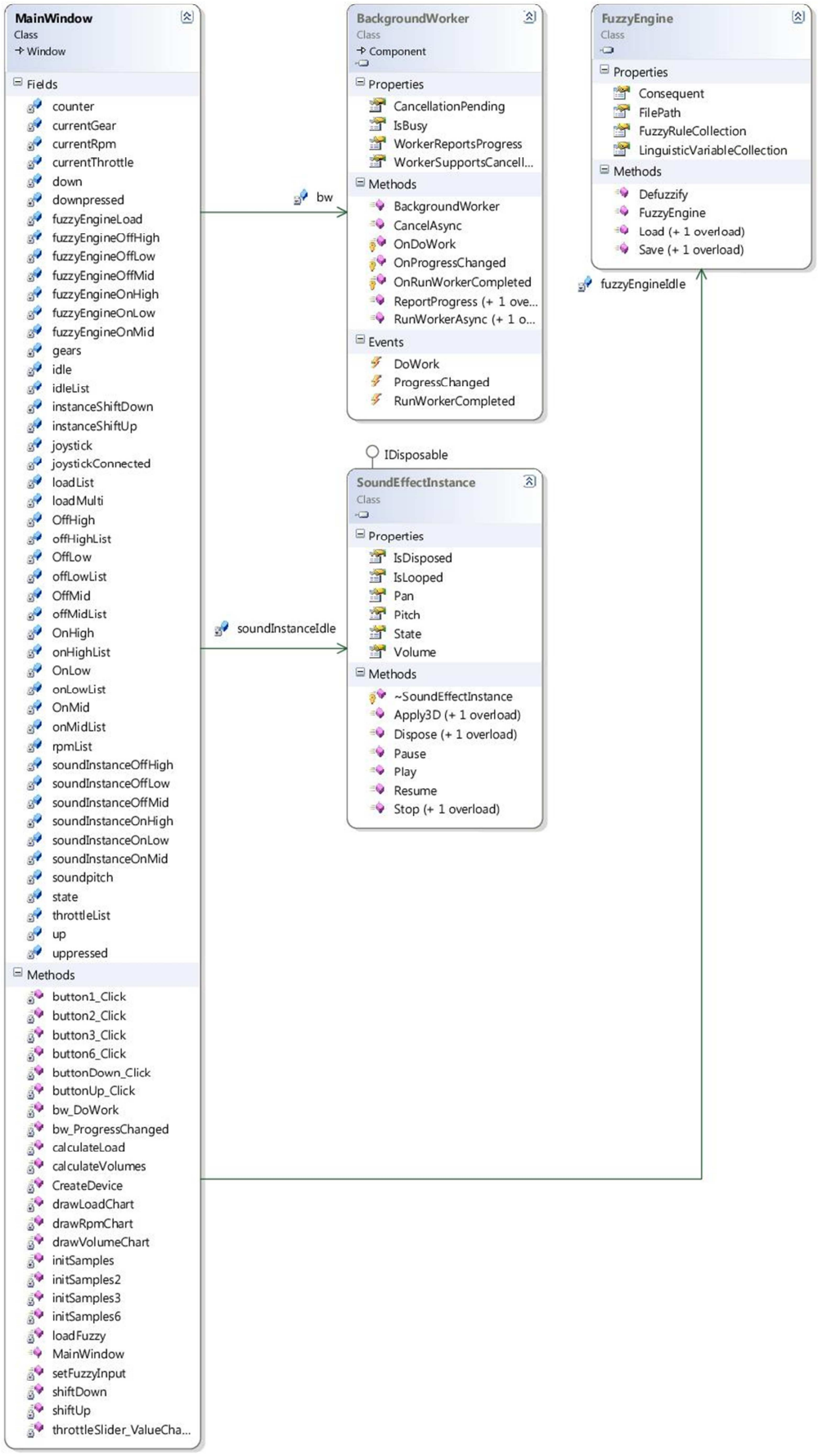
(Figure 9)

Programming Overview

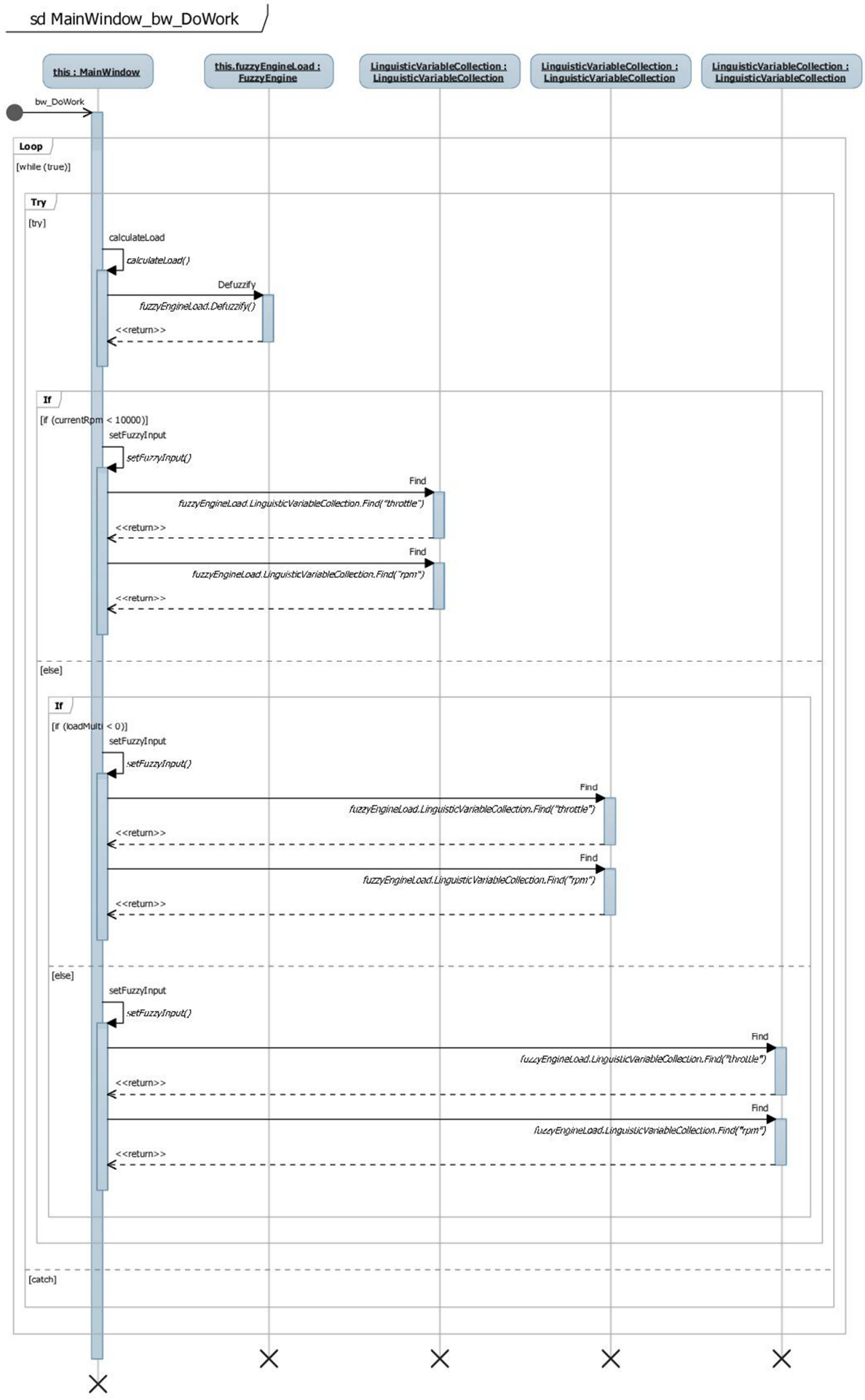
Simplistic flow diagram

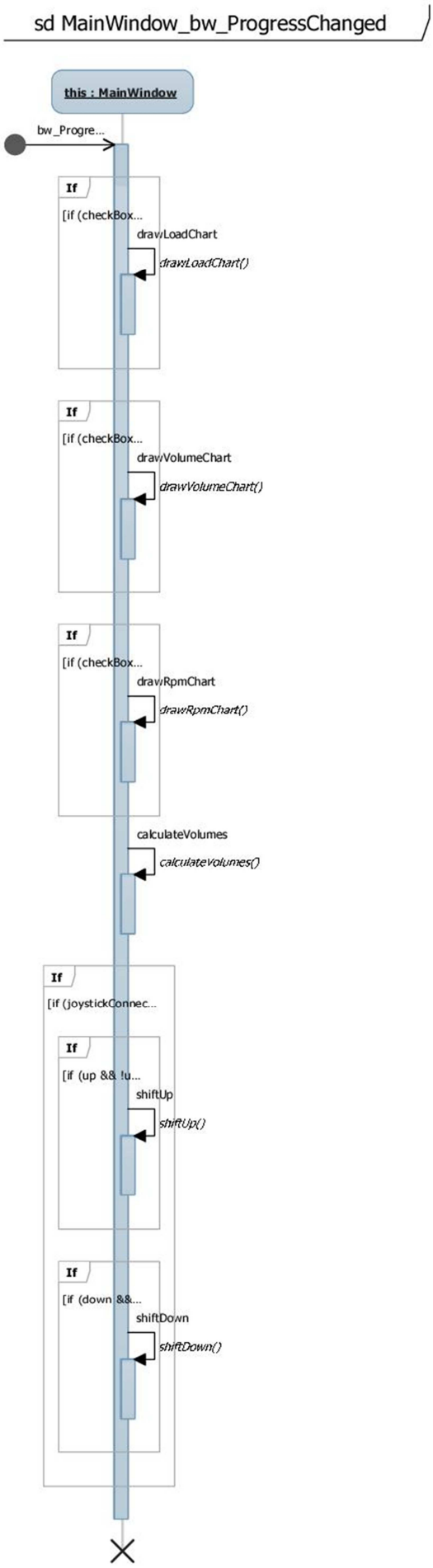


Class diagram

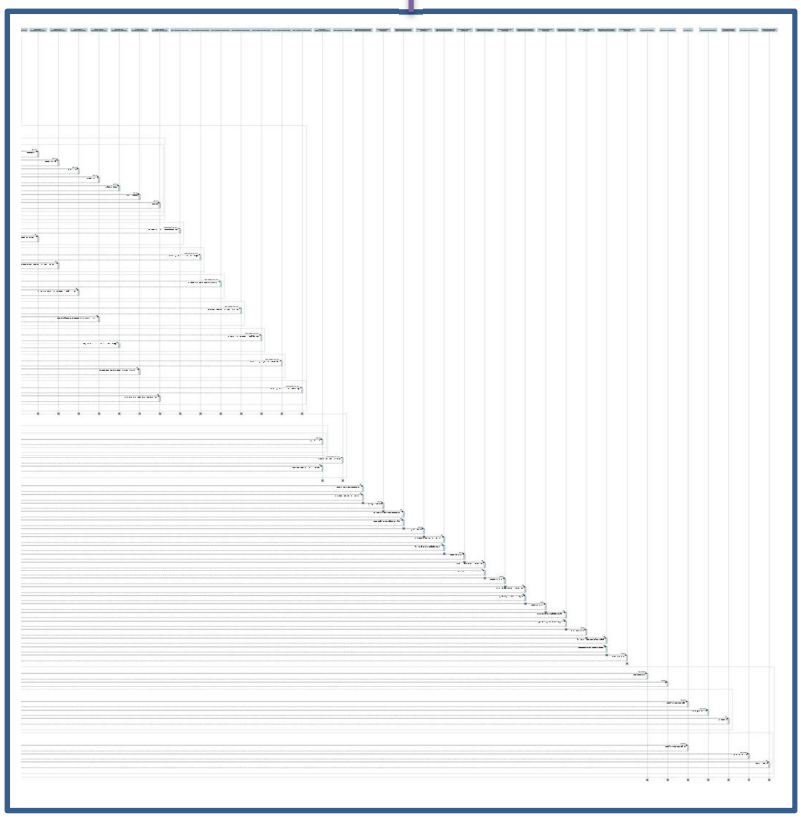


Sequence diagrams (Background worker)

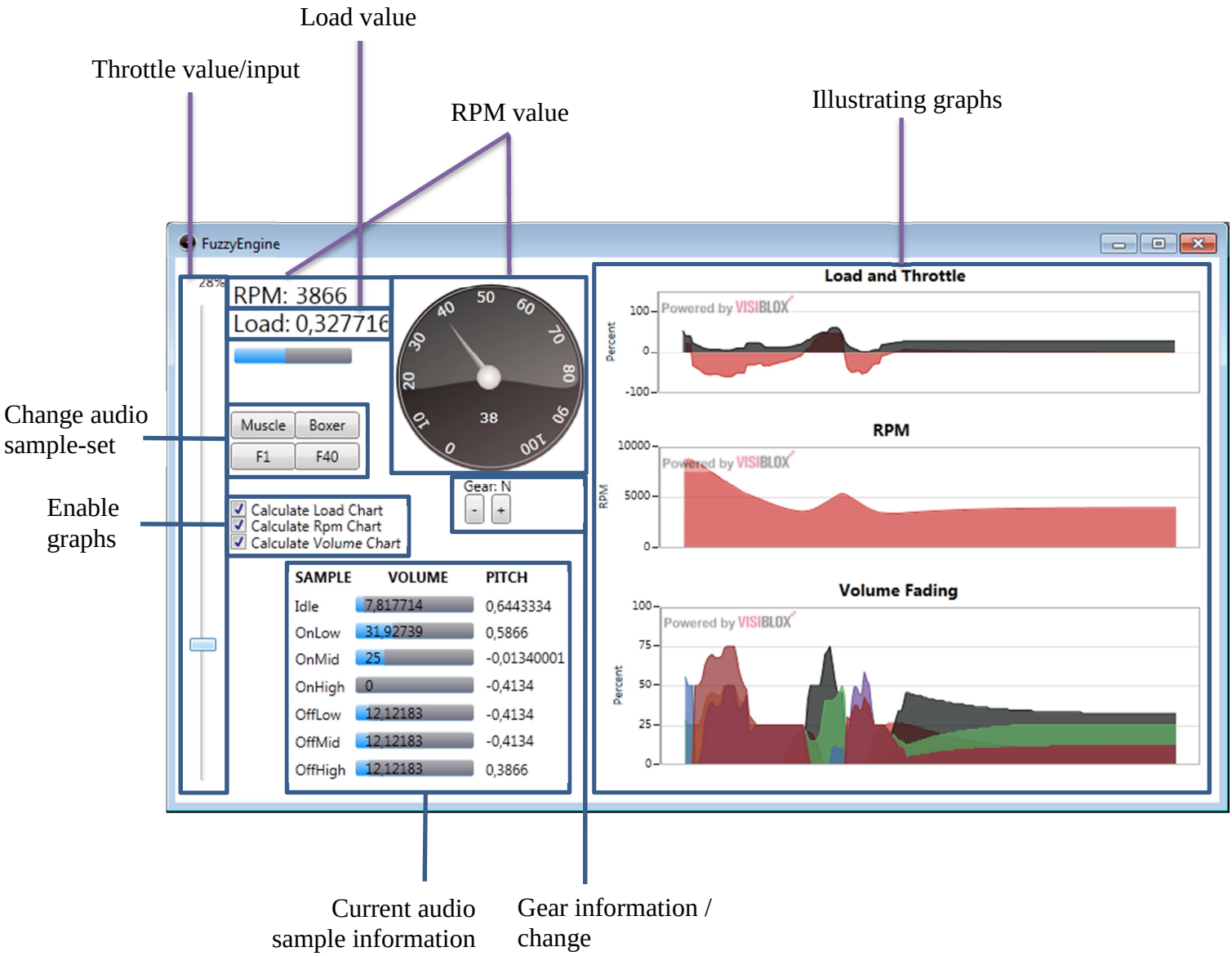




Full progressChanged()
sequence-diagram



Graphical user interface



Within the GUI it is possible to input throttle value as well as changing gears in real-time. In order to illustrate the dependency between volume fading, rpm, load and throttle graphs have been implemented and synchronised, so that every value-change can be traced at the exact same horizontal position.

Fuzzy implementation

In this approach, fuzzy inferece systems are described in associated FCL XML files.
An FCL (Fuzzy Control Language) file is separated into different definition blocks (INTERNATIONAL ELECTROTECHNICAL COMMISSION).

Examination of the fuzzy inference system FCL file to calculate the engine load vector:

- **FUNCTION BLOCK** start of block
  - *<FUNCTION_BLOCK>*
- **VAR_INPUT** – defining input variable and range
  - *<VAR_INPUT NAME="throttle" TYPE="REAL" RANGE="0 100" />*
  - *<VAR_INPUT NAME="rpm" TYPE="REAL" RANGE="0 10000" />*
- **VAR_OUTPUT** – defining output variable and range
  - *<VAR_OUTPUT NAME="load" TYPE="REAL" RANGE="-100 150" />*
- **FUZZIFY** – linguistic terms definition
  - *<FUZZIFY NAME="throttle">*
    <TERM NAME="verylow" POINTS="0 0 0 25" />
    <TERM NAME="low" POINTS="0 25 25 50" />
    <TERM NAME="mid" POINTS="25 50 50 75" />
    <TERM NAME="high" POINTS="50 75 75 100" />
    <TERM NAME="veryhigh" POINTS="75 100 100 100" />
    </FUZZIFY>
  - *<FUZZIFY NAME="rpm">*
    <TERM NAME="low" POINTS="900 1500 1500 5000" />
    <TERM NAME="mid" POINTS="999 5000 5000 10000" />
    <TERM NAME="high" POINTS="5000 10000 10000 10000" />
    <TERM NAME="idle" POINTS="700 900 900 1100" />
    <TERM NAME="idletoolow" POINTS="-100 400 400 900" />
    <TERM NAME="idletoohigh" POINTS="900 1100 1100 1250" />
    </FUZZIFY>
- **DEFUZZIFY** – defining defuzzify method, accumulation method (= result aggregation) and linguistic terms definition
  - *<DEFUZZIFY METHOD="**CoG**" ACCU="**MAX**" NAME="load">*
    <TERM NAME="fastdecreasing" POINTS="-100 -90 -90 -50" />
    <TERM NAME="between" POINTS="-10 30 30 80" />
    <TERM NAME="fastincreasing" POINTS="70 90 90 140" />
    <TERM NAME="decreasing" POINTS="-70 -30 -30 10" />
    <TERM NAME="increasing" POINTS="30 70 70 100" />
    <TERM NAME="turbo" POINTS="90 140 140 150" />
    <TERM NAME="zero" POINTS="-10 0 0 10" />
    <TERM NAME="slightincreasing" POINTS="0 5 5 10" />
    <TERM NAME="slightdecreasing" POINTS="-10 -5 -5 0" />
    </DEFUZZIFY>
- **RULEBLOCK** – defining AND, OR (min and max **= deMorgan's Law**) and rules
  - *<RULEBLOCK AND="MIN" OR="MAX">*
    <RULE NUMBER="1" TEXT="IF (throttle IS verylow) AND (rpm IS low) THEN load IS decreasing" />
    <RULE NUMBER="2" TEXT="IF (throttle IS low) AND (rpm IS low) THEN load IS between" />
    <RULE NUMBER="3" TEXT="IF (throttle IS mid) AND (rpm IS low) THEN load IS increasing" />
    <RULE NUMBER="4" TEXT="IF (throttle IS high) AND (rpm IS low) THEN load IS increasing" />
    <RULE NUMBER="5" TEXT="IF (throttle IS veryhigh) AND (rpm IS low) THEN load IS increasing" />
    <RULE NUMBER="6" TEXT="IF (throttle IS verylow) AND (rpm IS mid) THEN load IS fastdecreasing" />
    (…)
    <RULE NUMBER="21" TEXT="IF (throttle IS low) AND (rpm IS idle) THEN load IS between" />
    <RULE NUMBER="22" TEXT="IF (throttle IS veryhigh) AND (rpm IS idle) THEN load IS increasing" />
    </RULEBLOCK>
- **/ FUNCTION BLOCK** end of the block
  - </FUNCTION_BLOCK>

Possible defuzzification methods of an FCL file:
(INTERNATIONAL ELECTROTECHNICAL COMMISSION)

- COG Centre of Gravity
- COGS Centre of Gravity for Singletons
- COA Centre of Area
- LM Left Most Maximum
- RM Right Most Maximum

To fulfill de Morgan's Law, the algorithms for operators AND and OR shall be used pair-wise e.g. MAX shall be used for OR if MIN is used for AND.
Possible paired algorithms:

operator **OR**		operator **AND**	
keyword for **Algorithm**	**Algorithm**	keyword for **Algorithm**	**Algorithm**
MAX	Max (m1(x), m2(x))	MIN	Min(m1(x), m2(x))
ASUM	m1(x)+m2(x) - m1(x) m2(x)	PROD	m1(x) m2(x)
BSUM	Min(1, m1(x) + m2(x))	BDIF	Max (0, m1(x) + m2(x) -1)

(INTERNATIONAL ELECTROTECHNICAL COMMISSION)

By changing the methods and algorithms in the FCL, different outcomes can be testet. Unfortunately, this could have been implemented in the GUI. In Fact, the standard parameters of all inference systems of this assignment are CoG for deffuzification methods and OR=MAX, AND=MIN for the rule set algorithms.

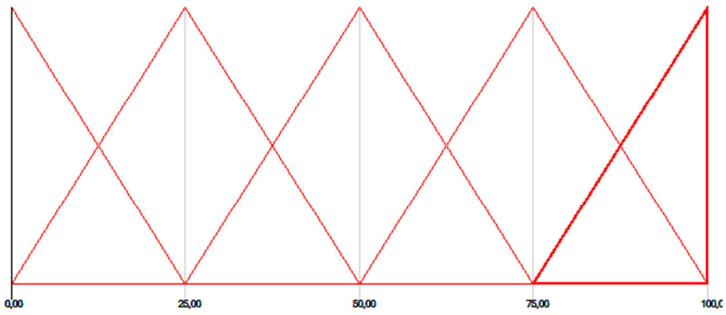
Engine load

This inference systems determines how fast the engine accerlates or deaccerlates. It also trys to balance the engine around an idle rpm value, when throttle is 0%.
To create a realistic feel of engine speed acceleration and deceleration, the FCL file had to be adjusted several times. The outcome of these adjustments feels very close to realistic engine behaviour.

Input variables

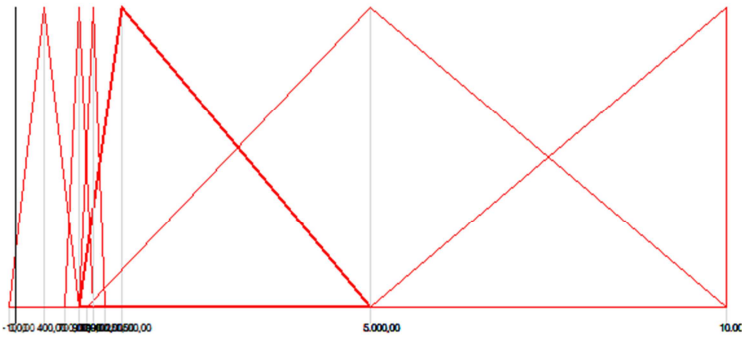
Throttle - Takes the throttle position value in percent (0-100)

Name	**X0**	**X1**	**X2**	**X3**
verylow	0	0	0	25
low	0	25	25	50
mid	25	50	50	75
high	50	75	75	100
veryhigh	75	100	100	100



Rpm - Takes the current rpm value (-100 – 10000)

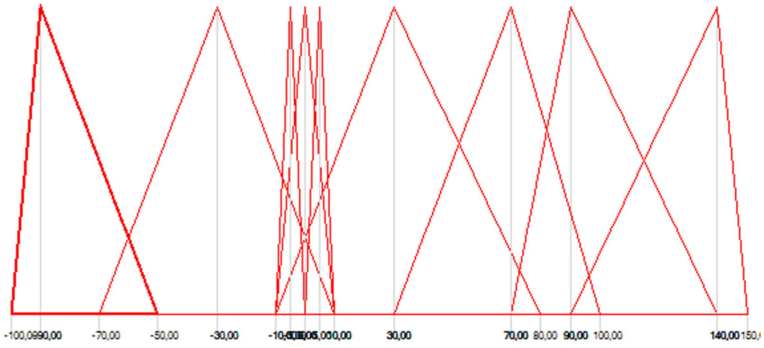
Name	**X0**	**X1**	**X2**	**X3**
low	900	1500	1500	5000
mid	999	5000	5000	1000
high	5000	10000	10000	10000
idle	700	900	900	1100
idletoolow	-100	400	400	900
idletoohigh	900	1100	1100	1250



Output variable

Load - Returns a load vector value (-100 – 150)

Name	X0	X1	X2	X3
fastdecreasing	-100	-90	-90	-50
between	-10	30	30	80
fastincreasing	70	90	90	140
decreasing	-70	-30	-30	10
increasing	30	70	70	100
turbo	90	140	140	150
zero	-10	0	0	10
slightincreasing	0	5	5	10
slightdecreasing	-10	-5	-5	0



Rules

1. IF (throttle IS verylow) AND (rpm IS low) THEN load IS decreasing
2. IF (throttle IS low) AND (rpm IS low) THEN load IS between
3. IF (throttle IS mid) AND (rpm IS low) THEN load IS increasing
4. IF (throttle IS high) AND (rpm IS low) THEN load IS increasing
5. IF (throttle IS veryhigh) AND (rpm IS low) THEN load IS increasing
6. IF (throttle IS verylow) AND (rpm IS mid) THEN load IS fastdecreasing
7. IF (throttle IS low) AND (rpm IS mid) THEN load IS decreasing
8. IF (throttle IS mid) AND (rpm IS mid) THEN load IS increasing
9. IF (throttle IS high) AND (rpm IS mid) THEN load IS increasing
10. IF (throttle IS veryhigh) AND (rpm IS mid) THEN load IS fastincreasing
11. IF (throttle IS verylow) AND (rpm IS high) THEN load IS fastdecreasing
12. IF (throttle IS mid) AND (rpm IS high) THEN load IS between
13. IF (throttle IS high) AND (rpm IS high) THEN load IS increasing
14. IF (throttle IS veryhigh) AND (rpm IS high) THEN load IS turbo
15. IF (throttle IS mid) AND (rpm IS mid) THEN load IS between
16. IF (throttle IS low) AND (rpm IS high) THEN load IS decreasing
17. IF (throttle IS veryhigh) AND (rpm IS high) THEN load IS turbo
18. IF (throttle IS verylow) AND (rpm IS idle) THEN load IS slightincreasing
19. IF (throttle IS verylow) AND (rpm IS idletoolow) THEN load IS slightincreasing
20. IF (throttle IS verylow) AND (rpm IS idletoohigh) THEN load IS slightdecreasing
21. IF (throttle IS low) AND (rpm IS idle) THEN load IS between
22. IF (throttle IS veryhigh) AND (rpm IS idle) THEN load IS increasing

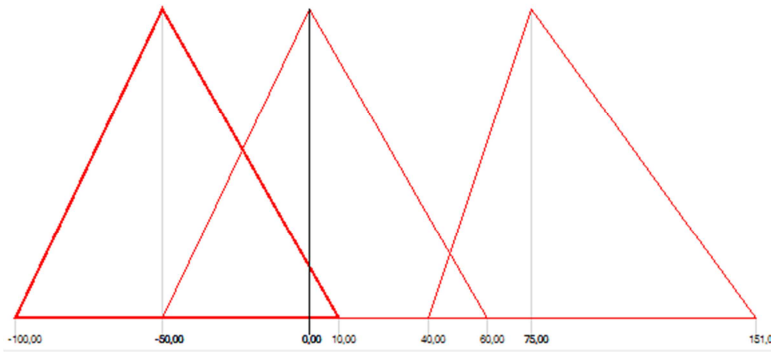
Audio Sample volumes

In this assignment, 7 audio samples are used, therefore 7 inference systems had to be set up, in order to calculate each audio sample volume individually. I will analyse the fuzzy inference system for the idle audio sample, which represents the engine at an idle state (see the plain FCL files in the appendix).

Input Variables

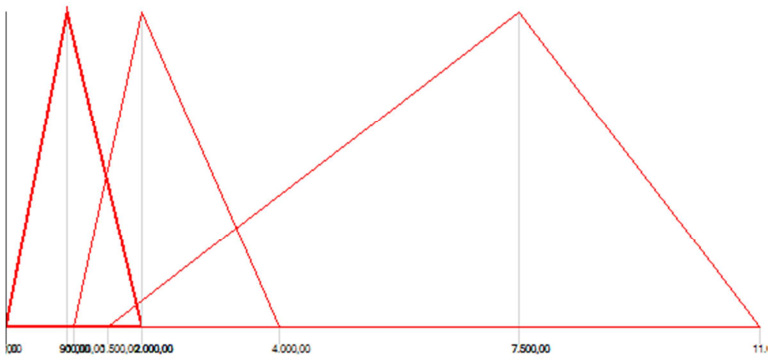
Load – takes the current load vector value (-100 – 151)

Name	X0	X1	X2	X3
low	-100	-50	-50	10
mid	-50	0	0	60
high	40	75	75	151



Rpm – takes the current rpm value (-1 – 11000)

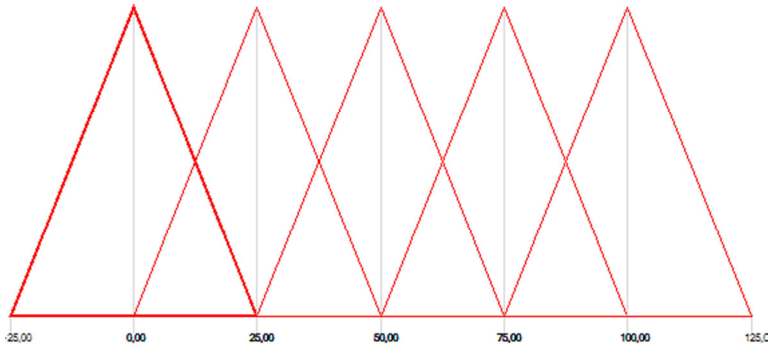
Name	X0	X1	X2	X3
low	-1	900	900	2000
mid	1000	2000	2000	4000
high	1500	7500	7500	11000



Output variable

Volume – returns the volume value (-25 – 125)

Name	X0	X1	X2	X3
verylow	-25	0	0	25
low	0	25	25	50
mid	25	50	50	75
high	50	75	75	100
veryhigh	75	100	100	125



Rules

1. IF (load IS low) AND (rpm IS low) THEN volume IS high
2. IF (load IS low) AND (rpm IS mid) THEN volume IS mid
3. IF (load IS low) AND (rpm IS high) THEN volume IS verylow
4. IF (load IS mid) AND (rpm IS low) THEN volume IS high
5. IF (load IS mid) AND (rpm IS mid) THEN volume IS mid
6. IF (load IS mid) AND (rpm IS high) THEN volume IS verylow
7. IF (load IS high) AND (rpm IS low) THEN volume IS high
8. IF (load IS high) AND (rpm IS mid) THEN volume IS low
9. IF (load IS high) AND (rpm IS high) THEN volume IS verylow

Possible Improvements

Fuzzy logic library

Due to this assignment, I encountered, that the dotFuzzy Library does obviously not differ between changes of specific elements in the FCL file. When changing the defuzzify method, accumulation method, aggregation method or the rule algorithms, it seems that the outcome is always the same. Furthermore, when defining unrelated strings, like “xyz”, the program does not notice at all. I have already emailed the developers of this library, to at least tell me which methods are used by default. (Based on their online samples it seems to be what I have described above).

The only possible way to improve the fuzzy engine behind this program is to change the whole library, in order to create a deeper fuzzy logic approach. Unfortunately the choice of accurate .NET libraries is very small. Moreover only 2 major libraries were found.

- dotFuzzy
  - Used in this project, very few configuration options
  - Undetailed documentation
  - Reads FCL files
  - Last stable release in 2009

- FuzzyNET (SourceForge)
  - Implements mangani and sugeno methods
  - Does not support FCL files
  - Last stable release in 2009

To implement FuzzyNET, the whole initiation progress has to be adapted, moving from FCL files to hard-coded fuzzy inference system parameters, which have to be set up in the c# code.

Real life approach

To improve the overall outcome and satisfy end-users, the program is designed to take engine values either by the calculated simulation, or (with a little adaption) to take load and rpm directly from a real engine. This could be accomplished by reading the ODB-II (On-board diagnostics) CAN-Bus in modern cars. This bus serves PIDs (Parameter ID) values which would fit into the assignments approach (Wikipedia).

Usable PIDs:

- 0C – Engine RPM
- 10 – MAF air flow rate (Mass flow sensor)
- 11 – throttle position

With help of an ODB-II scanner, an accurate sound emulator could be accomplished.
This could lead to a standard low-end car engine, sounding like a V12 or V8 engine, while connected to a handheld or laptop device.

This would probably be the first time, someone tried to emulate engine sound without directly connecting sensors to the engine.

Conclusion

With this assignment, I was able to learn much about engine sound engineering, .NET libraries and of course fuzzy logic. I liked the challenge to achieve a fuzzy logic approach, which no one has ever done before.
In my researches, I was not able to determine any use of fuzzy logic in game/engine sound engineering at all.

The idea was pretty simple, due to the module lessons, I developed a feel for what could be possible. I was not quite sure if the simulation of an engine, just by setting up 7 fuzzy logic inference systems with accurate rules is enough to convince car enthusiast, but for as far as I know, the output of this program does come pretty close to current racing simulations.

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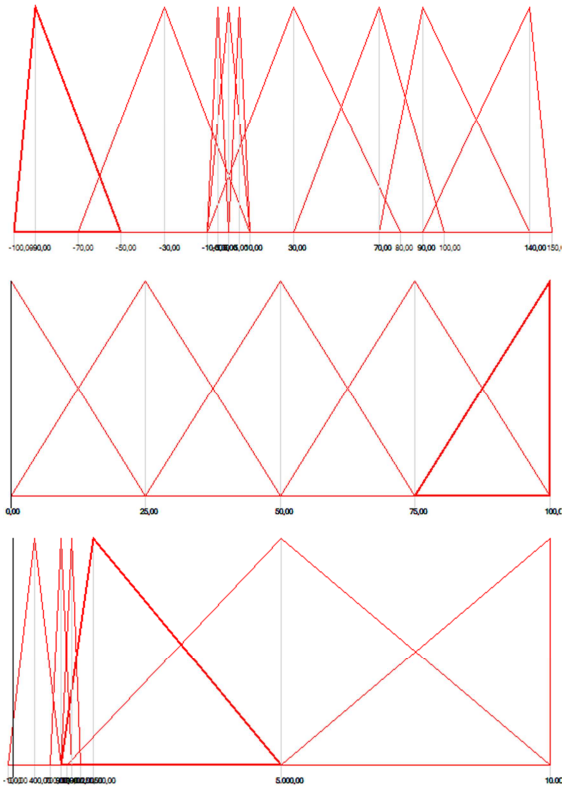
Appendix

FCL Files

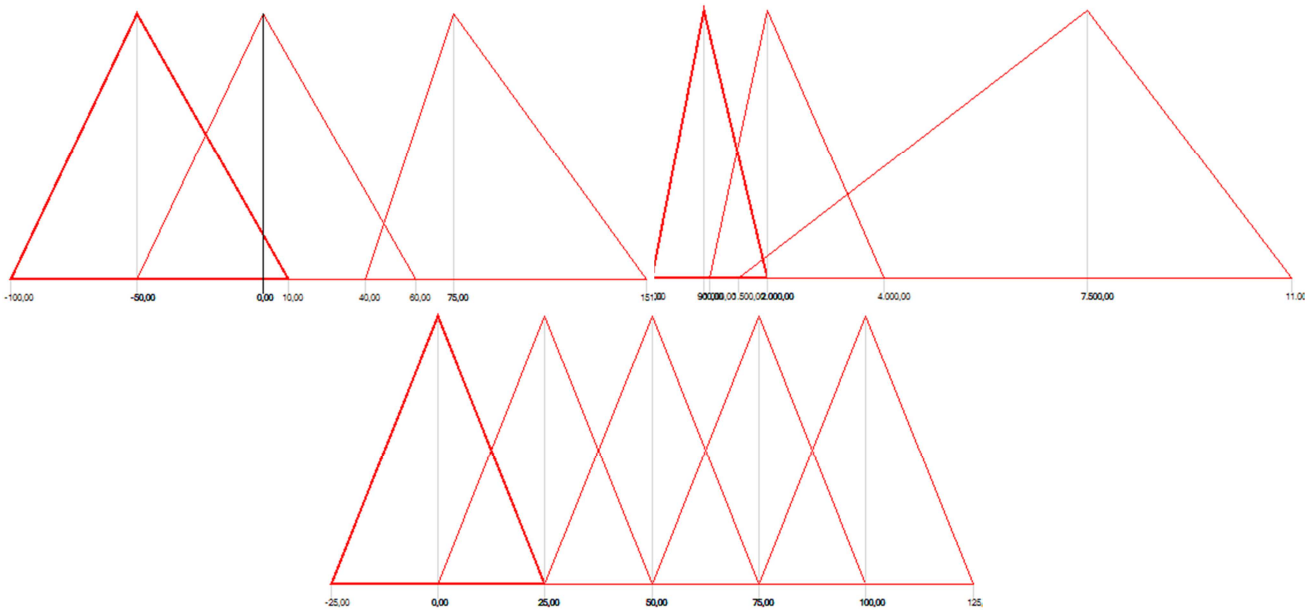
engineLoad.xml



```
<?xml version="1.0" encoding="utf-8" standalone="yes"?>
<FUNCTION_BLOCK>
  <VAR_INPUT NAME="throttle" TYPE="REAL" RANGE="0 100" />
  <VAR_INPUT NAME="rpm" TYPE="REAL" RANGE="-100 10000" />
  <VAR_OUTPUT NAME="load" TYPE="REAL" RANGE="-100 150" />
  <FUZZIFY NAME="throttle">
    <TERM NAME="verylow" POINTS="0 0 0 25" />
    <TERM NAME="low" POINTS="0 25 25 50" />
    <TERM NAME="mid" POINTS="25 50 50 75" />
    <TERM NAME="high" POINTS="50 75 75 100" />
    <TERM NAME="veryhigh" POINTS="75 100 100 100" />
  </FUZZIFY>
  <FUZZIFY NAME="rpm">
    <TERM NAME="low" POINTS="900 1500 1500 5000" />
    <TERM NAME="mid" POINTS="999 5000 5000 10000" />
    <TERM NAME="high" POINTS="5000 10000 10000 10000" />
    <TERM NAME="idle" POINTS="700 900 900 1100" />
    <TERM NAME="idletoolow" POINTS="-100 400 400 900" />
    <TERM NAME="idletoohigh" POINTS="900 1100 1100 1250" />
  </FUZZIFY>
  <DEFUZZIFY METHOD="COG" ACCU="MAX" NAME="load">
    <TERM NAME="fastdecreasing" POINTS="-100 -90 -90 -50" />
    <TERM NAME="between" POINTS="-10 30 30 80" />
    <TERM NAME="fastincreasing" POINTS="70 90 90 140" />
    <TERM NAME="decreasing" POINTS="-70 -30 -30 10" />
    <TERM NAME="increasing" POINTS="30 70 70 100" />
    <TERM NAME="turbo" POINTS="90 140 140 150" />
    <TERM NAME="zero" POINTS="-10 0 0 10" />
    <TERM NAME="slightincreasing" POINTS="0 5 5 10" />
    <TERM NAME="slightdecreasing" POINTS="-10 -5 -5 0" />
  </DEFUZZIFY>
  <RULEBLOCK AND="MIN" OR="MAX">
    <RULE NUMBER="1" TEXT="IF (throttle IS verylow) AND (rpm IS low) THEN load IS decreasing" />
    <RULE NUMBER="2" TEXT="IF (throttle IS low) AND (rpm IS low) THEN load IS between" />
    <RULE NUMBER="3" TEXT="IF (throttle IS mid) AND (rpm IS low) THEN load IS increasing" />
    <RULE NUMBER="4" TEXT="IF (throttle IS high) AND (rpm IS low) THEN load IS increasing" />
    <RULE NUMBER="5" TEXT="IF (throttle IS veryhigh) AND (rpm IS low) THEN load IS increasing" />
    <RULE NUMBER="6" TEXT="IF (throttle IS verylow) AND (rpm IS mid) THEN load IS fastdecreasing" />
    <RULE NUMBER="7" TEXT="IF (throttle IS low) AND (rpm IS mid) THEN load IS decreasing" />
    <RULE NUMBER="8" TEXT="IF (throttle IS mid) AND (rpm IS mid) THEN load IS increasing" />
    <RULE NUMBER="9" TEXT="IF (throttle IS high) AND (rpm IS mid) THEN load IS increasing" />
    <RULE NUMBER="10" TEXT="IF (throttle IS veryhigh) AND (rpm IS mid) THEN load IS fastincreasing" />
    <RULE NUMBER="11" TEXT="IF (throttle IS verylow) AND (rpm IS high) THEN load IS fastdecreasing" />
    <RULE NUMBER="12" TEXT="IF (throttle IS mid) AND (rpm IS high) THEN load IS between" />
    <RULE NUMBER="13" TEXT="IF (throttle IS high) AND (rpm IS high) THEN load IS increasing" />
    <RULE NUMBER="14" TEXT="IF (throttle IS veryhigh) AND (rpm IS high) THEN load IS turbo" />
    <RULE NUMBER="15" TEXT="IF (throttle IS mid) AND (rpm IS mid) THEN load IS between" />
    <RULE NUMBER="16" TEXT="IF (throttle IS low) AND (rpm IS high) THEN load IS decreasing" />
    <RULE NUMBER="17" TEXT="IF (throttle IS veryhigh) AND (rpm IS high) THEN load IS turbo" />
    <RULE NUMBER="18" TEXT="IF (throttle IS verylow) AND (rpm IS idle) THEN load IS slightincreasing" />
    <RULE NUMBER="19" TEXT="IF (throttle IS verylow) AND (rpm IS idletoolow) THEN load IS slightincreasing" />
    <RULE NUMBER="20" TEXT="IF (throttle IS verylow) AND (rpm IS idletoohigh) THEN load IS slightdecreasing" />
    <RULE NUMBER="21" TEXT="IF (throttle IS low) AND (rpm IS idle) THEN load IS between" />
    <RULE NUMBER="22" TEXT="IF (throttle IS veryhigh) AND (rpm IS idle) THEN load IS increasing" />
  </RULEBLOCK>
</FUNCTION_BLOCK>
```

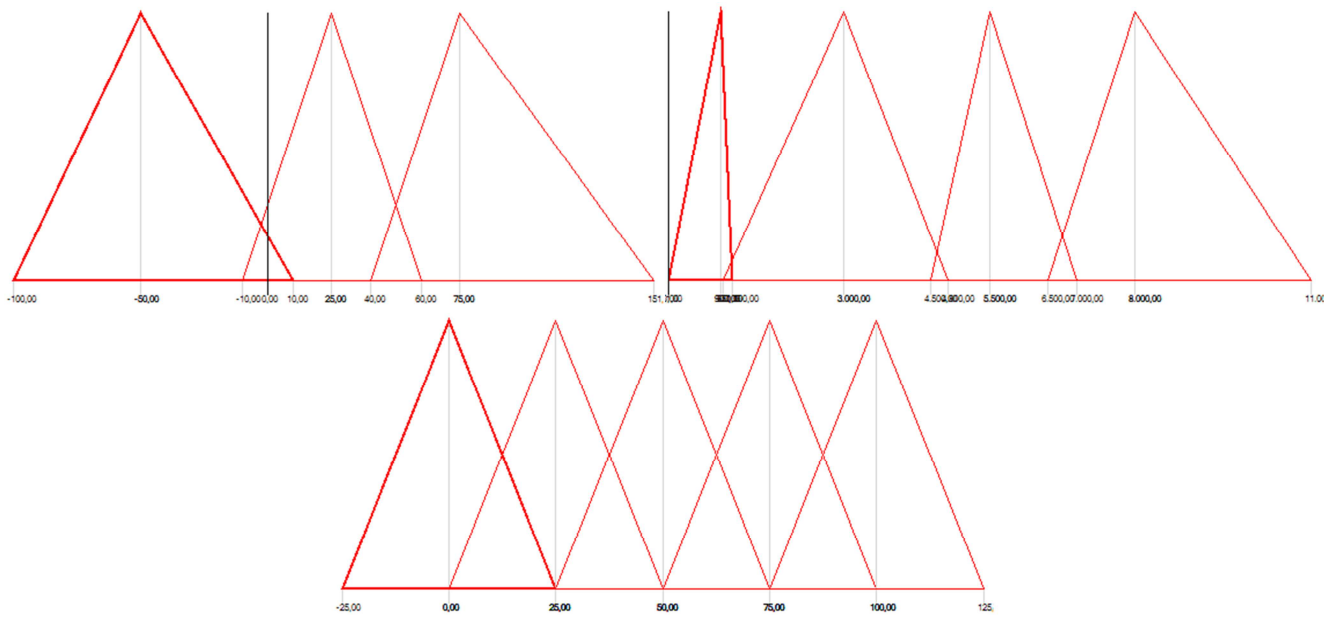
engineVolIdle.xml

```
<?xml version="1.0" encoding="utf-8" standalone="yes"?>
<FUNCTION_BLOCK>
  <VAR_INPUT NAME="load" TYPE="REAL" RANGE="-100 151" />
  <VAR_INPUT NAME="rpm" TYPE="REAL" RANGE="-1 11000" />
  <VAR_OUTPUT NAME="volume" TYPE="REAL" RANGE="-25 125" />
  <FUZZIFY NAME="load">
    <TERM NAME="low" POINTS="-100 -50 -50 10" />
    <TERM NAME="mid" POINTS="-50 0 0 60" />
    <TERM NAME="high" POINTS="40 75 75 151" />
  </FUZZIFY>
  <FUZZIFY NAME="rpm">
    <TERM NAME="low" POINTS="-1 900 900 2000" />
    <TERM NAME="mid" POINTS="1000 2000 2000 4000" />
    <TERM NAME="high" POINTS="1500 7500 7500 11000" />
  </FUZZIFY>
  <DEFUZZIFY METHOD="CoG" ACCU="MAX" NAME="volume">
    <TERM NAME="verylow" POINTS="-25 0 0 25" />
    <TERM NAME="low" POINTS="0 25 25 50" />
    <TERM NAME="mid" POINTS="25 50 50 75" />
    <TERM NAME="high" POINTS="50 75 75 100" />
    <TERM NAME="veryhigh" POINTS="75 100 100 125" />
  </DEFUZZIFY>
  <RULEBLOCK AND="MIN" OR="MAX">
    <RULE NUMBER="1" TEXT="IF (load IS low) AND (rpm IS low) THEN volume IS high" />
    <RULE NUMBER="2" TEXT="IF (load IS low) AND (rpm IS mid) THEN volume IS mid" />
    <RULE NUMBER="3" TEXT="IF (load IS low) AND (rpm IS high) THEN volume IS verylow" />
    <RULE NUMBER="4" TEXT="IF (load IS mid) AND (rpm IS low) THEN volume IS high" />
    <RULE NUMBER="5" TEXT="IF (load IS mid) AND (rpm IS mid) THEN volume IS mid" />
    <RULE NUMBER="6" TEXT="IF (load IS mid) AND (rpm IS high) THEN volume IS verylow" />
    <RULE NUMBER="7" TEXT="IF (load IS high) AND (rpm IS low) THEN volume IS high" />
    <RULE NUMBER="8" TEXT="IF (load IS high) AND (rpm IS mid) THEN volume IS low" />
    <RULE NUMBER="9" TEXT="IF (load IS high) AND (rpm IS high) THEN volume IS verylow" />
  </RULEBLOCK>
</FUNCTION_BLOCK>
```



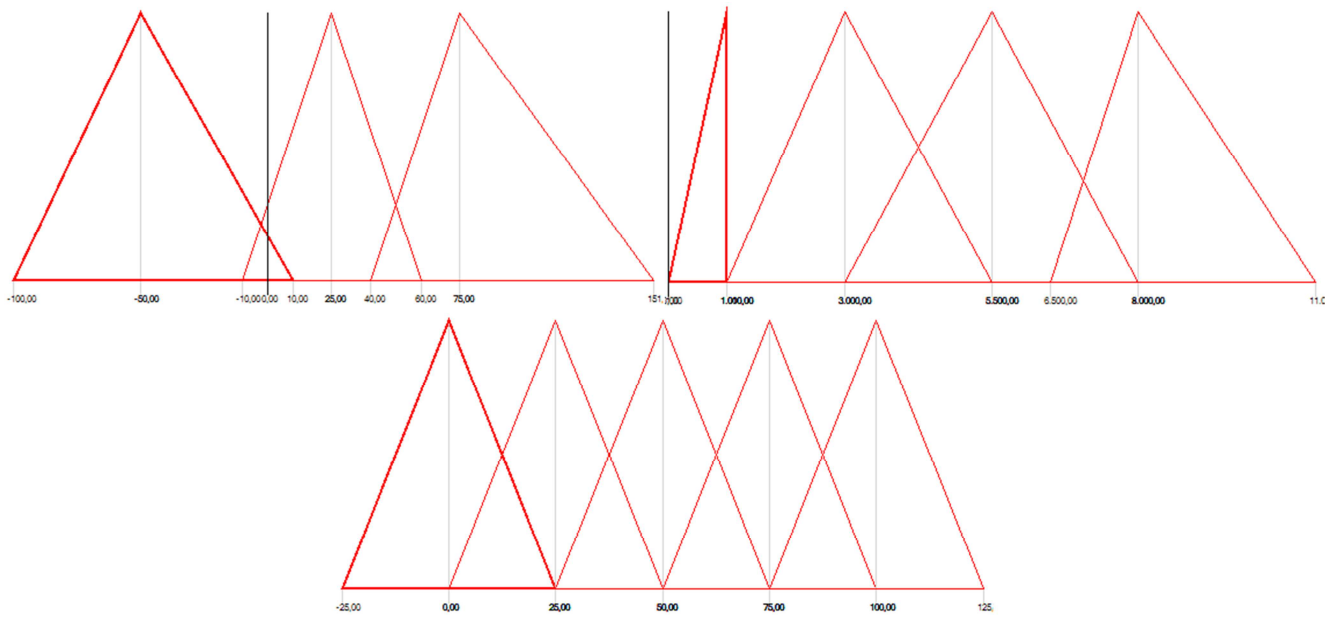
engineVolOnLow.xml

```
<?xml version="1.0" encoding="utf-8" standalone="yes"?>
<FUNCTION_BLOCK>
  <VAR_INPUT NAME="load" TYPE="REAL" RANGE="-100 151" />
  <VAR_INPUT NAME="rpm" TYPE="REAL" RANGE="-1 11000" />
  <VAR_OUTPUT NAME="volume" TYPE="REAL" RANGE="-25 125" />
  <FUZZIFY NAME="load">
    <TERM NAME="low" POINTS="-100 -50 -50 10" />
    <TERM NAME="mid" POINTS="-10 25 25 60" />
    <TERM NAME="high" POINTS="40 75 75 151" />
  </FUZZIFY>
  <FUZZIFY NAME="rpm">
    <TERM NAME="verylow" POINTS="-1 900 900 1100" />
    <TERM NAME="low" POINTS="950 3000 3000 4800" />
    <TERM NAME="mid" POINTS="4500 5500 5500 7000" />
    <TERM NAME="high" POINTS="6500 8000 8000 11000" />
  </FUZZIFY>
  <DEFUZZIFY METHOD="CoG" ACCU="MAX" NAME="volume">
    <TERM NAME="verylow" POINTS="-25 0 0 25" />
    <TERM NAME="low" POINTS="0 25 25 50" />
    <TERM NAME="mid" POINTS="25 50 50 75" />
    <TERM NAME="high" POINTS="50 75 75 100" />
    <TERM NAME="veryhigh" POINTS="75 100 100 125" />
  </DEFUZZIFY>
  <RULEBLOCK AND="MIN" OR="MAX">
    <RULE NUMBER="1" TEXT="IF (load IS low) AND (rpm IS low) THEN volume IS verylow" />
    <RULE NUMBER="2" TEXT="IF (load IS low) AND (rpm IS mid) THEN volume IS verylow" />
    <RULE NUMBER="3" TEXT="IF (load IS low) AND (rpm IS high) THEN volume IS verylow" />
    <RULE NUMBER="4" TEXT="IF (load IS mid) AND (rpm IS low) THEN volume IS mid" />
    <RULE NUMBER="5" TEXT="IF (load IS mid) AND (rpm IS mid) THEN volume IS low" />
    <RULE NUMBER="6" TEXT="IF (load IS mid) AND (rpm IS high) THEN volume IS verylow" />
    <RULE NUMBER="7" TEXT="IF (load IS high) AND (rpm IS low) THEN volume IS veryhigh" />
    <RULE NUMBER="8" TEXT="IF (load IS high) AND (rpm IS mid) THEN volume IS high" />
    <RULE NUMBER="9" TEXT="IF (load IS high) AND (rpm IS high) THEN volume IS verylow" />
    <RULE NUMBER="10" TEXT="IF (load IS low) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="11" TEXT="IF (load IS mid) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="12" TEXT="IF (load IS high) AND (rpm IS verylow) THEN volume IS verylow" />
  </RULEBLOCK>
</FUNCTION_BLOCK>
```



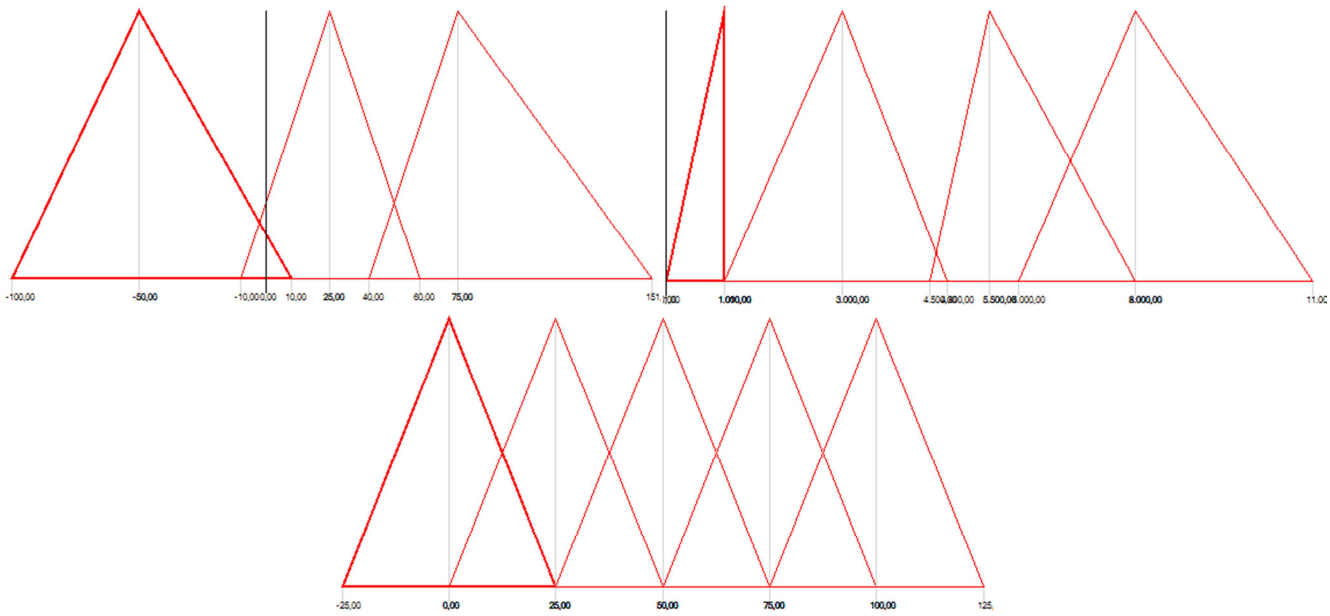
engineVolOnMid.xml

```
<?xml version="1.0" encoding="utf-8" standalone="yes"?>
<FUNCTION_BLOCK>
  <VAR_INPUT NAME="load" TYPE="REAL" RANGE="-100 151" />
  <VAR_INPUT NAME="rpm" TYPE="REAL" RANGE="-1 11000" />
  <VAR_OUTPUT NAME="volume" TYPE="REAL" RANGE="-25 125" />
  <FUZZIFY NAME="load">
    <TERM NAME="low" POINTS="-100 -50 -50 10" />
    <TERM NAME="mid" POINTS="-10 25 25 60" />
    <TERM NAME="high" POINTS="40 75 75 151" />
  </FUZZIFY>
  <FUZZIFY NAME="rpm">
    <TERM NAME="verylow" POINTS="-1 1000 1000 1010" />
    <TERM NAME="low" POINTS="1010 3000 3000 5500" />
    <TERM NAME="mid" POINTS="3000 5500 5500 8000" />
    <TERM NAME="high" POINTS="6500 8000 8000 11000" />
  </FUZZIFY>
  <DEFUZZIFY METHOD="CoG" ACCU="MAX" NAME="volume">
    <TERM NAME="verylow" POINTS="-25 0 0 25" />
    <TERM NAME="low" POINTS="0 25 25 50" />
    <TERM NAME="mid" POINTS="25 50 50 75" />
    <TERM NAME="high" POINTS="50 75 75 100" />
    <TERM NAME="veryhigh" POINTS="75 100 100 125" />
  </DEFUZZIFY>
  <RULEBLOCK AND="MIN" OR="MAX">
    <RULE NUMBER="1" TEXT="IF (load IS low) AND (rpm IS low) THEN volume IS verylow" />
    <RULE NUMBER="2" TEXT="IF (load IS low) AND (rpm IS mid) THEN volume IS verylow" />
    <RULE NUMBER="3" TEXT="IF (load IS low) AND (rpm IS high) THEN volume IS verylow" />
    <RULE NUMBER="4" TEXT="IF (load IS mid) AND (rpm IS low) THEN volume IS verylow" />
    <RULE NUMBER="5" TEXT="IF (load IS mid) AND (rpm IS mid) THEN volume IS mid" />
    <RULE NUMBER="6" TEXT="IF (load IS mid) AND (rpm IS high) THEN volume IS low" />
    <RULE NUMBER="7" TEXT="IF (load IS high) AND (rpm IS low) THEN volume IS low" />
    <RULE NUMBER="8" TEXT="IF (load IS high) AND (rpm IS mid) THEN volume IS veryhigh" />
    <RULE NUMBER="9" TEXT="IF (load IS high) AND (rpm IS high) THEN volume IS mid" />
    <RULE NUMBER="10" TEXT="IF (load IS low) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="11" TEXT="IF (load IS mid) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="12" TEXT="IF (load IS high) AND (rpm IS verylow) THEN volume IS verylow" />
  </RULEBLOCK>
</FUNCTION_BLOCK>
```



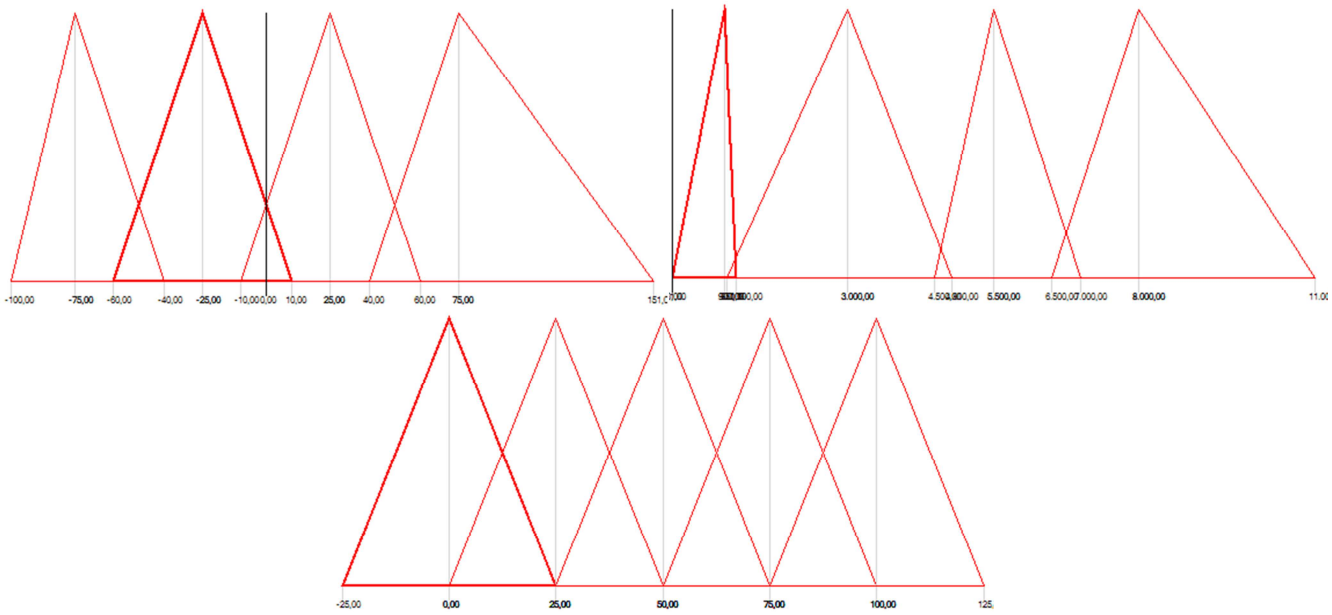
engineVolOnHigh.xml

```
<?xml version="1.0" encoding="utf-8" standalone="yes"?>
<FUNCTION_BLOCK>
  <VAR_INPUT NAME="load" TYPE="REAL" RANGE="-100 151" />
  <VAR_INPUT NAME="rpm" TYPE="REAL" RANGE="-1 11000" />
  <VAR_OUTPUT NAME="volume" TYPE="REAL" RANGE="-25 125" />
  <FUZZIFY NAME="load">
    <TERM NAME="low" POINTS="-100 -50 -50 10" />
    <TERM NAME="mid" POINTS="-10 25 25 60" />
    <TERM NAME="high" POINTS="40 75 75 151" />
  </FUZZIFY>
  <FUZZIFY NAME="rpm">
    <TERM NAME="verylow" POINTS="-1 1000 1000 1010" />
    <TERM NAME="low" POINTS="1010 3000 3000 4800" />
    <TERM NAME="mid" POINTS="4500 5500 5500 8000" />
    <TERM NAME="high" POINTS="6000 8000 8000 11000" />
  </FUZZIFY>
  <DEFUZZIFY METHOD="CoG" ACCU="MAX" NAME="volume">
    <TERM NAME="verylow" POINTS="-25 0 0 25" />
    <TERM NAME="low" POINTS="0 25 25 50" />
    <TERM NAME="mid" POINTS="25 50 50 75" />
    <TERM NAME="high" POINTS="50 75 75 100" />
    <TERM NAME="veryhigh" POINTS="75 100 100 125" />
  </DEFUZZIFY>
  <RULEBLOCK AND="MIN" OR="MAX">
    <RULE NUMBER="1" TEXT="IF (load IS low) AND (rpm IS low) THEN volume IS verylow" />
    <RULE NUMBER="2" TEXT="IF (load IS low) AND (rpm IS mid) THEN volume IS verylow" />
    <RULE NUMBER="3" TEXT="IF (load IS low) AND (rpm IS high) THEN volume IS verylow" />
    <RULE NUMBER="4" TEXT="IF (load IS mid) AND (rpm IS low) THEN volume IS verylow" />
    <RULE NUMBER="5" TEXT="IF (load IS mid) AND (rpm IS mid) THEN volume IS verylow" />
    <RULE NUMBER="6" TEXT="IF (load IS mid) AND (rpm IS high) THEN volume IS mid" />
    <RULE NUMBER="7" TEXT="IF (load IS high) AND (rpm IS low) THEN volume IS verylow" />
    <RULE NUMBER="8" TEXT="IF (load IS high) AND (rpm IS mid) THEN volume IS low" />
    <RULE NUMBER="9" TEXT="IF (load IS high) AND (rpm IS high) THEN volume IS veryhigh" />
    <RULE NUMBER="10" TEXT="IF (load IS low) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="11" TEXT="IF (load IS mid) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="12" TEXT="IF (load IS high) AND (rpm IS verylow) THEN volume IS verylow" />
  </RULEBLOCK>
</FUNCTION_BLOCK>
```



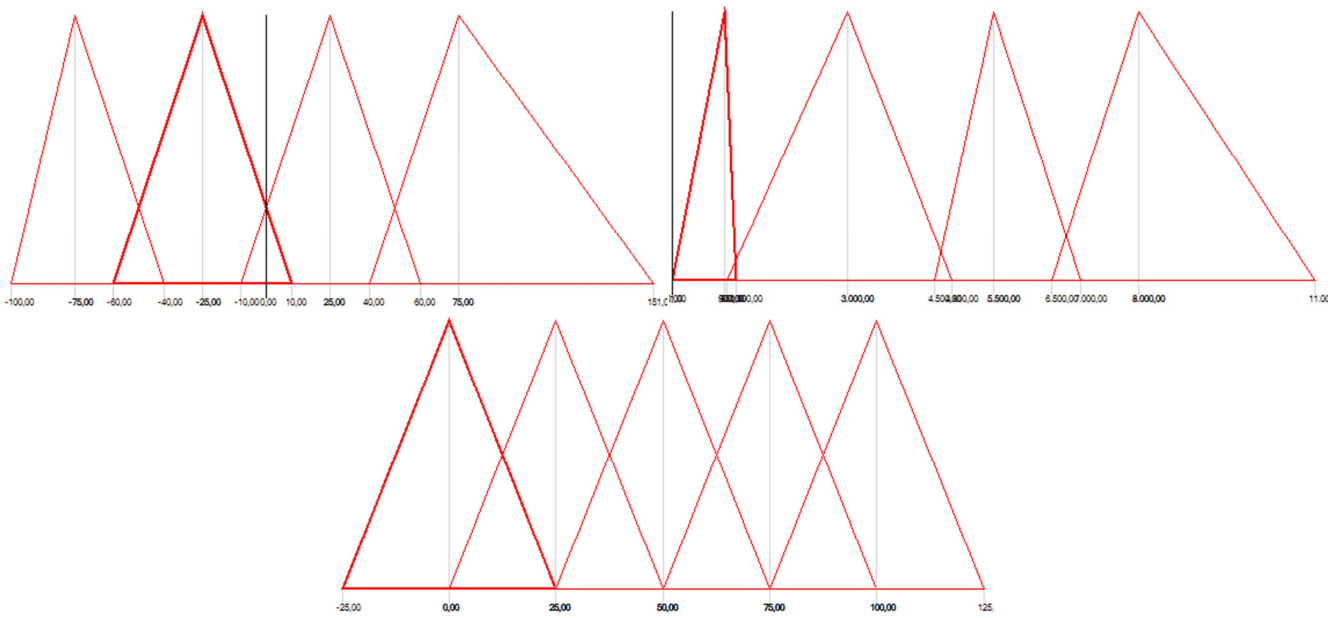
engineVolOffLow.xml

```
<?xml version="1.0" encoding="utf-8" standalone="yes"?>
<FUNCTION_BLOCK>
  <VAR_INPUT NAME="load" TYPE="REAL" RANGE="-100 151" />
  <VAR_INPUT NAME="rpm" TYPE="REAL" RANGE="-1 11000" />
  <VAR_OUTPUT NAME="volume" TYPE="REAL" RANGE="-25 125" />
  <FUZZIFY NAME="load">
    <TERM NAME="low" POINTS="-60 -25 -25 10" />
    <TERM NAME="verylow" POINTS="-100 -75 -75 -40" />
    <TERM NAME="mid" POINTS="-10 25 25 60" />
    <TERM NAME="high" POINTS="40 75 75 151" />
  </FUZZIFY>
  <FUZZIFY NAME="rpm">
    <TERM NAME="verylow" POINTS="-1 900 900 1100" />
    <TERM NAME="low" POINTS="950 2000 2000 3000" />
    <TERM NAME="mid" POINTS="2500 4000 4000 6000" />
    <TERM NAME="high" POINTS="5000 7500 7500 11000" />
  </FUZZIFY>
  <DEFUZZIFY METHOD="CoG" ACCU="MAX" NAME="volume">
    <TERM NAME="verylow" POINTS="-25 0 0 25" />
    <TERM NAME="low" POINTS="0 25 25 50" />
    <TERM NAME="mid" POINTS="25 50 50 75" />
    <TERM NAME="high" POINTS="50 75 75 100" />
    <TERM NAME="veryhigh" POINTS="75 100 100 125" />
  </DEFUZZIFY>
  <RULEBLOCK AND="MIN" OR="MAX">
    <RULE NUMBER="1" TEXT="IF (load IS low) AND (rpm IS low) THEN volume IS low" />
    <RULE NUMBER="2" TEXT="IF (load IS low) AND (rpm IS mid) THEN volume IS low" />
    <RULE NUMBER="3" TEXT="IF (load IS low) AND (rpm IS high) THEN volume IS low" />
    <RULE NUMBER="4" TEXT="IF (load IS mid) AND (rpm IS low) THEN volume IS verylow" />
    <RULE NUMBER="5" TEXT="IF (load IS mid) AND (rpm IS mid) THEN volume IS verylow" />
    <RULE NUMBER="6" TEXT="IF (load IS mid) AND (rpm IS high) THEN volume IS verylow" />
    <RULE NUMBER="7" TEXT="IF (load IS high) AND (rpm IS low) THEN volume IS verylow" />
    <RULE NUMBER="8" TEXT="IF (load IS high) AND (rpm IS mid) THEN volume IS verylow" />
    <RULE NUMBER="9" TEXT="IF (load IS high) AND (rpm IS high) THEN volume IS verylow" />
    <RULE NUMBER="10" TEXT="IF (load IS low) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="11" TEXT="IF (load IS mid) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="12" TEXT="IF (load IS high) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="13" TEXT="IF (load IS verylow) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="14" TEXT="IF (load IS verylow) AND (rpm IS low) THEN volume IS mid" />
    <RULE NUMBER="15" TEXT="IF (load IS verylow) AND (rpm IS mid) THEN volume IS mid" />
    <RULE NUMBER="16" TEXT="IF (load IS verylow) AND (rpm IS high) THEN volume IS mid" />
  </RULEBLOCK>
</FUNCTION_BLOCK>
```



EngineVolOffMid.xml

```
<?xml version="1.0" encoding="utf-8" standalone="yes"?>
<FUNCTION_BLOCK>
  <VAR_INPUT NAME="load" TYPE="REAL" RANGE="-100 151" />
  <VAR_INPUT NAME="rpm" TYPE="REAL" RANGE="-1 11000" />
  <VAR_OUTPUT NAME="volume" TYPE="REAL" RANGE="-25 125" />
  <FUZZIFY NAME="load">
    <TERM NAME="low" POINTS="-60 -25 -25 10" />
    <TERM NAME="verylow" POINTS="-100 -75 -75 -40" />
    <TERM NAME="mid" POINTS="-10 25 25 60" />
    <TERM NAME="high" POINTS="40 75 75 151" />
  </FUZZIFY>
  <FUZZIFY NAME="rpm">
    <TERM NAME="verylow" POINTS="-1 900 900 1300" />
    <TERM NAME="low" POINTS="950 2000 2000 3000" />
    <TERM NAME="mid" POINTS="2500 4000 4000 6000" />
    <TERM NAME="high" POINTS="5000 7500 7500 11000" />
  </FUZZIFY>
  <DEFUZZIFY METHOD="CoG" ACCU="MAX" NAME="volume">
    <TERM NAME="verylow" POINTS="-25 0 0 25" />
    <TERM NAME="low" POINTS="0 25 25 50" />
    <TERM NAME="mid" POINTS="25 50 50 75" />
    <TERM NAME="high" POINTS="50 75 75 100" />
    <TERM NAME="veryhigh" POINTS="75 100 100 125" />
  </DEFUZZIFY>
  <RULEBLOCK AND="MIN" OR="MAX">
    <RULE NUMBER="1" TEXT="IF (load IS low) AND (rpm IS low) THEN volume IS low" />
    <RULE NUMBER="2" TEXT="IF (load IS low) AND (rpm IS mid) THEN volume IS low" />
    <RULE NUMBER="3" TEXT="IF (load IS low) AND (rpm IS high) THEN volume IS verylow" />
    <RULE NUMBER="4" TEXT="IF (load IS mid) AND (rpm IS low) THEN volume IS verylow" />
    <RULE NUMBER="5" TEXT="IF (load IS mid) AND (rpm IS mid) THEN volume IS verylow" />
    <RULE NUMBER="6" TEXT="IF (load IS mid) AND (rpm IS high) THEN volume IS verylow" />
    <RULE NUMBER="7" TEXT="IF (load IS high) AND (rpm IS low) THEN volume IS verylow" />
    <RULE NUMBER="8" TEXT="IF (load IS high) AND (rpm IS mid) THEN volume IS verylow" />
    <RULE NUMBER="9" TEXT="IF (load IS high) AND (rpm IS high) THEN volume IS verylow" />
    <RULE NUMBER="10" TEXT="IF (load IS low) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="11" TEXT="IF (load IS mid) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="12" TEXT="IF (load IS high) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="13" TEXT="IF (load IS verylow) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="14" TEXT="IF (load IS verylow) AND (rpm IS low) THEN volume IS mid" />
    <RULE NUMBER="15" TEXT="IF (load IS verylow) AND (rpm IS mid) THEN volume IS high" />
    <RULE NUMBER="16" TEXT="IF (load IS verylow) AND (rpm IS high) THEN volume IS mid" />
  </RULEBLOCK>
</FUNCTION_BLOCK>
```



EngineVolOffHigh.xml

```
<?xml version="1.0" encoding="utf-8" standalone="yes"?>
<FUNCTION_BLOCK>
  <VAR_INPUT NAME="load" TYPE="REAL" RANGE="-100 150" />
  <VAR_INPUT NAME="rpm" TYPE="REAL" RANGE="-1 11000" />
  <VAR_OUTPUT NAME="volume" TYPE="REAL" RANGE="-25 125" />
  <FUZZIFY NAME="load">
    <TERM NAME="low" POINTS="-60 -25 -25 10" />
    <TERM NAME="mid" POINTS="-10 25 25 60" />
    <TERM NAME="high" POINTS="40 75 75 150" />
    <TERM NAME="verylow" POINTS="-100 -75 -75 -40" />
  </FUZZIFY>
  <FUZZIFY NAME="rpm">
    <TERM NAME="verylow" POINTS="-1 1000 1000 1010" />
    <TERM NAME="low" POINTS="1010 2000 2000 3000" />
    <TERM NAME="mid" POINTS="2500 4000 4000 6000" />
    <TERM NAME="high" POINTS="5000 7500 7500 11000" />
  </FUZZIFY>
  <DEFUZZIFY METHOD="CoG" ACCU="MAX" NAME="volume">
    <TERM NAME="verylow" POINTS="-25 0 0 25" />
    <TERM NAME="low" POINTS="0 25 25 50" />
    <TERM NAME="mid" POINTS="25 50 50 75" />
    <TERM NAME="high" POINTS="50 75 75 100" />
    <TERM NAME="veryhigh" POINTS="75 100 100 125" />
  </DEFUZZIFY>
  <RULEBLOCK AND="MIN" OR="MAX">
    <RULE NUMBER="1" TEXT="IF (load IS low) AND (rpm IS low) THEN volume IS verylow" />
    <RULE NUMBER="2" TEXT="IF (load IS low) AND (rpm IS mid) THEN volume IS low" />
    <RULE NUMBER="3" TEXT="IF (load IS low) AND (rpm IS high) THEN volume IS mid" />
    <RULE NUMBER="4" TEXT="IF (load IS mid) AND (rpm IS low) THEN volume IS verylow" />
    <RULE NUMBER="5" TEXT="IF (load IS mid) AND (rpm IS mid) THEN volume IS verylow" />
    <RULE NUMBER="6" TEXT="IF (load IS mid) AND (rpm IS high) THEN volume IS verylow" />
    <RULE NUMBER="7" TEXT="IF (load IS high) AND (rpm IS low) THEN volume IS verylow" />
    <RULE NUMBER="8" TEXT="IF (load IS high) AND (rpm IS mid) THEN volume IS verylow" />
    <RULE NUMBER="9" TEXT="IF (load IS high) AND (rpm IS high) THEN volume IS verylow" />
    <RULE NUMBER="10" TEXT="IF (load IS low) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="11" TEXT="IF (load IS mid) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="12" TEXT="IF (load IS high) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="13" TEXT="IF (load IS verylow) AND (rpm IS verylow) THEN volume IS verylow" />
    <RULE NUMBER="14" TEXT="IF (load IS verylow) AND (rpm IS low) THEN volume IS verylow" />
    <RULE NUMBER="15" TEXT="IF (load IS verylow) AND (rpm IS mid) THEN volume IS mid" />
    <RULE NUMBER="16" TEXT="IF (load IS verylow) AND (rpm IS high) THEN volume IS high" />
  </RULEBLOCK>
</FUNCTION_BLOCK>
```