Vehicle Emission Measurement

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Combustion Process

Ideal Combustion $\lambda = 1$

Diagram showing the process of ideal combustion with fuel, oxygen, and carbon dioxide.
Combustion process

**Lean Mixture \( \lambda > 1 \)**

- Fuel
- O\(_2\)
- CO\(_2\)

**Rich Mixture \( \lambda < 1 \)**

- Fuel
- O\(_2\)
- CO\(_2\)
- CO
- Unburnt Fuel
Combustion gas: oxygen ($O_2$)

- $O_2$ levels inverse of CO levels without air injection system

- Lean Mixture: $O_2$ ↑

- Rich Mixture: $O_2$ ↓

- $O_2$ content increases sharply as $\lambda > 1$

© http://www.youtube.com/watch?v=nlhDLnTGMAE
Combustion gas: carbon dioxide (CO$_2$)

- Result of complete combustion
- Overall combustion and catalytic converter efficiency
- Not a pass or fail gas
- CO$_2$: 12-16%
Combustion gas: carbon monoxide (CO)

- Incomplete combustion
- Excess fuel = rich mixture
- Partially burnt fuel
- Catalytic converter requires air/fuel ratio to vary lean to rich
  - Pre-catalytic converter: CO < 1.5%
  - After catalytic converter: CO ~ 0%
- Feedback carburetted engine ran rich at idle: CO ~ 9%
Combustion gas: hydrocarbons (HC)

• Unburned fuel due to incomplete combustion

• All engines produce HC:
  ➢ Pre-catalytic converter: 150-300 ppm
  ➢ After catalytic converter: ~0 ppm

• Wasted fuel
  ➢ 1% partially burnt fuel produce 200 ppm HC
Combustion gas: oxides of nitrogen (NO\textsubscript{X})

- Primary contributor of ozone
- Formed under high T & P: not formed at idle or light loads

- Lean mixture at high T: excess O\textsubscript{2} molecules combine to form NO\textsubscript{X}
- Exhaust gas recirculation (EGR): O\textsubscript{2}↓ and T
Combustion gas: oxides of sulphur (SO$_x$)

- High sulphur (S) content in fuel
  - Reduction in S content reduces emissions in exhaust
  - Marine engines have higher contribution

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Combustion particles-particulate matter (PM)

• Formed in combustion cylinder and in the exhaust system of the vehicle.
• Mostly attributable to heavy duty diesel vehicles

Mix (condensed) liquid & solid: Organic or Inorganic

• Sulphates
• Nitrates
• Ammonia
• Sodium chloride
• Black Carbon
• Mineral dust
• Water
Source apportionment: what are the sources of urban air pollution?

Impact of air pollution in Africa?

Sub-Saharan Africa
Air pollution
Both sexes, All ages

Deaths


## Petrol and Diesel Engines

<table>
<thead>
<tr>
<th>Petrol Engine</th>
<th>Diesel Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spark Ignition</td>
<td>Compression Ignition</td>
</tr>
<tr>
<td>Fuel/Air premixed before compression</td>
<td>Fuel/Air not premixed</td>
</tr>
<tr>
<td>Lower efficiency &amp; Lighter</td>
<td>Higher efficiency-High compression ratio &amp; Heavier</td>
</tr>
<tr>
<td>AFR:14.7 (predetermined)</td>
<td>AFR: 20-100/1 (air injected not controlled)</td>
</tr>
<tr>
<td>Emissions: More fuel, &gt;CO$_2$, less NO$_X$ and low PM</td>
<td>Emissions: less fuel, &lt;CO$_2$, &gt;NO$_X$ Higher PM</td>
</tr>
<tr>
<td>Pollutants: CO, HC, NO$_X$</td>
<td>Pollutants: NO$_X$, PM, Smoke</td>
</tr>
</tbody>
</table>
Units of measurement

**Gases**
- $O_2$: %
- $CO_2$: %
- $CO$: %
- $HC$: ppm
- $NO_x$: ppm

**PM**
- Particulate Mass ($\mu g/m^3$)
- Particulate Number (#/km)

**Smoke:**
- Opacity: %
- Smoke density: $m^{-1}$

**Engine:** $\lambda$, RPM, T, P
Vehicle Emission Legislation

- Emission limits
- Test cycles
- Test and Measurement Specifications
- Result Calculation and reporting specifications

Standards
- Regulations

Time

Emission Standards
- Chassis Dyno
- Engine Dyno

Global Harmonization
USA Harmonization
Use of PEMS to measure gases & PM

GPS & weather probe

Exhaust Flow Meter (EFM)

Weighing

Flow tube

Gas bench: CO/CO2 (NDIR) NOx (NDUV), THC (FID)

Heated sample line

Exhaust sample

power supply 110 VAC, 220 VAC or 12 VDC
# EU Emission legislation

## Light Duty

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## Positive Ignition Engines (Gasoline)

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## Compression Ignition Engines (Diesel)

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## Test cycles

### EU-I+II

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### EU-III+IV

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## Reduction Levels

- **Moderate Reduction (<30%)**
- **Large Reduction (>30%)**
Vehicle technology and fuel quality

Adopted ICCT, 2012
Selective Catalytic Reduction (SCR)
Diesel engine control emissions technology

- Reduces NOx (~90%) using urea as a reductant within a catalyst system
- End product: N\textsubscript{2}, H\textsubscript{2}O and small CO\textsubscript{2}

3 Way Catalytic converter (TWC)
Petrol engine control emissions technology

- Most vehicles sold have TWC
- Use of TWCs with an oxygen sensor-based closed-loop fuel delivery system
- Simultaneous conversion of the three criteria pollutants-HC, CO, and NOx
## Inspection & Maintenance

### I/M Standards-based on distribution of emissions levels

- Set Inspection fees to support I/M programs

### Phased Approach: Learning Adaptation Capacity building

- I/M requirement for operating vehicle + Linked to vehicle registration
- Capacity building for all actors in I/M

### I/M Requirements for Various Tests:

<table>
<thead>
<tr>
<th>Test</th>
<th>CO</th>
<th>HC</th>
<th>NO\textsubscript{x}</th>
<th>PM</th>
<th>Smoke</th>
<th>Cost</th>
<th>Time</th>
<th>Where?</th>
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<tbody>
<tr>
<td>Idle Test</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>low</td>
<td>fast</td>
<td>UK, EU</td>
</tr>
<tr>
<td>2-Speed idle Test</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>low</td>
<td>fast</td>
<td>UK, EU</td>
</tr>
<tr>
<td>Snap or Free acceleration Test</td>
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<td></td>
<td></td>
<td>X</td>
<td></td>
<td>low</td>
<td>fast</td>
<td>California, SA</td>
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<tr>
<td>IM 240</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>High</td>
<td>Medium</td>
<td>USA</td>
</tr>
<tr>
<td>Full load</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>High</td>
<td>Medium</td>
<td>EU, USA, Japan</td>
</tr>
</tbody>
</table>

**Note:** The table indicates which emissions (CO, HC, NO\textsubscript{x}, PM, Smoke) are tested for each test, along with the cost (low, high), time (fast, medium), and the geographical location(s) where each test is applicable.
## EU Emission I/M Standards

Source: EU directives 96/96 EC and 2001/9/EC

<table>
<thead>
<tr>
<th>Year</th>
<th>CO standard (%)</th>
<th>Lambda (λ)</th>
<th>Test (Petrol)</th>
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<tbody>
<tr>
<td>&lt; 1986</td>
<td>4.5</td>
<td>-</td>
<td>Idle</td>
</tr>
<tr>
<td>&gt; 1986</td>
<td>3.5</td>
<td>-</td>
<td>Idle</td>
</tr>
<tr>
<td>With Catalytic converter</td>
<td>0.5</td>
<td>-</td>
<td>Idle</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.97 &lt; λ &lt; 1.03</td>
<td>2 speed idle</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Turbocharged</th>
<th>Naturally aspirant</th>
<th>Test (Diesel)</th>
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</thead>
<tbody>
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<td>&lt; 1980</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>&gt; 1980</td>
<td>3.0 m⁻¹</td>
<td>2.5 m⁻¹</td>
<td>Free acceleration</td>
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</table>
## UK Emission MOT standards

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<th>Test</th>
<th>Type (Petrol)</th>
<th>Pass or Fail</th>
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<tbody>
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<td>All</td>
<td>Visual Inspection</td>
<td>Visual</td>
<td>Black smoke/dense blue</td>
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<tr>
<td>&gt;1975</td>
<td>Standard Emissions</td>
<td>Gas Analyzer (non-catalyst test)</td>
<td>CO :3.5%-4.5% HC: 1200ppm</td>
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<tr>
<td>&gt;1992</td>
<td>Basic Emissions</td>
<td>Gas Analyzer &amp; EC Fast Idle</td>
<td>CO&lt;0.2% HC&lt;200ppm 0.97 &lt; λ &lt;1.03</td>
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<tr>
<td></td>
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<td>Normal Idle</td>
<td>CO &lt;0.3%</td>
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<table>
<thead>
<tr>
<th>Year</th>
<th>Turbocharged Opacity (m⁻¹)</th>
<th>Normal Opacity(m⁻¹)</th>
<th>Test (Diesel)</th>
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<td>&lt;1979</td>
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<td>-</td>
<td>Visual</td>
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<td>1979-2008</td>
<td>3</td>
<td>2.5</td>
<td>Diesel fast pass</td>
</tr>
<tr>
<td>&gt; 2008</td>
<td>1.5</td>
<td>1.5</td>
<td>Diesel fast pass</td>
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</table>
Decentralized: ~20,000 local car repair garages

Test:
- Vehicle safety
- Road worthiness
- Exhaust emissions

Age: 3 years old
Annual test Cost: £30-£130
Failure: notice & repair
Re-test: free or reduced fee (defect/time)
Time: 45-60 min, 2 technicians
California Air Resources Board (ARB)

• Heavy-duty trucks and buses: control excessive smoke emissions & prevent tampering (>6000lb)

• Test-Society of Automotive Engineers (SAE) J1667 snap acceleration procedure-opacity measurement

• Test using PEMS

<table>
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<th>Allowable levels of Smoke Opacity</th>
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<tbody>
<tr>
<td>All post 1991 or newer engines</td>
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<tr>
<td>All pre-1991 engines</td>
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- Periodic Smoke Inspection Program (PSIP)
- Heavy-Duty Vehicle Inspection Program (HDVIP)
South Africa-Cape Town Emission Legislation

- Vehicles: Compression ignition (Diesel)
- Dark smoke (2010): Light absorption $\geq 20\%$
- BP Hartridge smoke meter

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<th>2010</th>
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<td>Naturally aspirated</td>
<td>60 HSU 2.125m$^{-1}$</td>
<td>50HSU 1.61m$^{-1}$ 18.57%</td>
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<tr>
<td>Turbocharged</td>
<td>66 HSU 2.51m$^{-1}$</td>
<td>56HSU 1.191m$^{-1}$ 21.57%</td>
</tr>
</tbody>
</table>
Framework for Vehicle Emission Measurement

State
Atmospheric emission concentrations

Macro-scale: National
Road Transport Emissions Inventory

Meso-scale: Regional
city fleet, activity data

Micro-scale: per vehicle and per person
High spatial and temporal data and personal exposure patterns

Impact
Climate
Agriculture
Health
Economic

Pressure
Vehicle emissions (GHG, SLCP, air pollutants)
Traffic Congestion

Drivers
Increased population
Economic growth
Increase demand for transport
Urbanization
Consumption patterns
Institutional framework

Response
Fuel Economy & Vehicle Emission standards
Decarbonisation of transport
Sustainable transport and mobility
1. Micro-scale per vehicle: real-world vehicle emission measurement

1. Micro-scale per vehicle: real-world vehicle emission data
2. Meso-scale: urban vehicle fleet characteristics and activity

2. Meso-scale: urban vehicle fleet characteristics and activity

3. Macro-scale: Assessment of the impact of road transport policies on air pollution and greenhouse gas emissions in Kenya


Types of public service vehicle

M1: Toyota Probox

M2: Matatu 14 seater

L3e: bodaboda

N2/NM2/M3-Matatu 29, 33, 37, 51 seater