A BULK MODEL OF EMISSIONS FROM SOUTH AFRICAN DIESEL COMMERCIAL VEHICLES

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1. INTRODUCTION

Air pollution has become synonymous with the modern urban environment. Such is the current scale of human activity in production, processing and transport that globally any industrialised city will be prone to some form of air pollution. Air pollution is often insidious and disperses quickly from the site of contamination to offer a potential threat to the health and quality of life of people over a wide area. So called mobile source emissions or emissions from vehicles are recognised as a significant source of pollution in urban environments (2) and legislation of ever increasing severity has been implemented in Europe, the United States and Japan to limit the emissions from vehicles. South African cities are no exception to this trend with pollution levels having at times been measured as exceeding World Health Organisation (WHO) Guidelines (2).

A number of initiatives have resulted from concerns about air quality in South Africa most notable perhaps being the Brown Haze Study and the Vehicle Emissions Project (VEP) (19,26,30) commissioned by the Department of Minerals and Energy and the Department of Environment and Tourism. The VEP consisted of Five Phases as follows:

Phase 1: The gathering and evaluation of ambient air quality data within South Africa. The gathering and evaluation of existing data on motor vehicle inventory in South Africa

Phase 2: The establishment of exhaust emission levels from a local in-service car fleet and the understanding of the combination of the fuel, engine and altitude influences on local vehicle emissions,

Phase 3 The development or adoption of an urban atmosphere air quality model. The model aims to relate motor vehicle emission to ambient concentrations of both primary and secondary pollutants. Use of the model for scenario planning.

Phase 4 The formation of policy, based on the pollution levels predicted by the model.

Phase 5: The development of a plan of action to ensure conformation with the new requirements.

The definition of the *local in-service car fleet* in Phase 2 includes commercial vehicles powered by heavy-duty diesel engines that account for the contribution of the commercial transport industry to urban air pollution. Phases 1 and 2 have been completed but Phase 3 has been delayed due to problems with funding (22).

The study described in this paper, attempts in some measure to tackle the objectives of Phase 3 as regards the emissions of compression ignition (diesel) engine commercial vehicles only. The data measured from the heavy-duty diesel engine study (26) of the VEP and the limited sample of light commercial vehicle data from the passenger vehicle study (30) was augmented by two other sources and used as input to a so-called bulk emissions or "inventory" model. This is simply a calculation of the total emissions produced by the vehicle park over a fixed period, usually a year and takes no account of the dispersion of the pollutants into the atmosphere. Such models are currently used elsewhere to attain the exact objectives of Phase 3, for example the IPIECA Toolkit(5), a sophisticated inventory model that accounts for both mobile and stationary source emissions and resolves these into cost to the community. The principle of the simple inventory approach is that if a bulk model is sensitive to technology, fuel and population drivers, policy and growth scenarios can easily be simulated and their effects on total emissions quantified with reasonable assurance of accuracy. Given that the objective of policy making is to decide on optimal and cost effective actions, not predict to an exact degree the outcome of these actions, such an approach it may be argued, is sufficient to prioritise available policy actions. Moreover dispersion modelling is notorious for it's mathematical complexity and high cost arising from the density of data required as input to achieve a reliable result.

Note to the reader: Please refer to ***Annexure*** *1 on the last page for definitions of abbreviations.*

Diab and Barnard (10) have proposed a novel non-linear empirical modelling technique for use in South African cities that promises accurate predictions without requiring the density of spatial time resolved data of the first principles Eularian approach. Even this methodology however requires some degree of ambient sampling and is particularly dependent on traffic flow data(10), neither of which are widely available for South African cities.

It is therefore proposed that a comprehensive and continually updated bulk emissions model will be a useful short to medium term tool with which to formulate air quality policy and management decisions. This paper describes proposals for the overall design and database inputs for fuel usage and vehicle population characteristics. Certain key scenarios were also identified and modelled. Some conclusions have been drawn based on comparison of the results to the baseline emissions.

The VEP engine emissions database was augmented in critical areas by work published by the Energy Research Institute and Mossgas (11) and by contract work done by the former Centre for Automotive Engineering at the University of Stellenbosch for BP South Africa (27). The former work was used to generate a data set for engines using synthetic fuel at sea level. The latter data has been used with the kind permission of BP Southern Africa and enabled the generation of a data set for turbo-intercooled engines. Both of these fundamental aspects were omitted from the VEP work. The experimental work from all sources was supervised by the author and performed using the same apparatus. None of the test data is presented as part of this paper due to constraints of space. All results were calculated for 1998, corresponding to the latest statistics available for vehicles in the emissions database.

2. OBJECTIVES OF THE STUDY

Objectives for the modelling study were defined as follows:

- Create a simple robust bulk emissions model that will yield gross annual emissions and emission factors for the South African vehicle population.

- The model should reflect the variability of the VEP data and supplementary data ie: Account for the following characteristics of the vehicle population:

  - Fuel use; synthetic or crude
  - Altitude or sea-level operation
  - Aspiration; natural, turbocharged or turbo-intercooled
  - Engine displacement
  - Technology level of naturally aspirated engines

- The model should facilitate scenarios of emissions given changes to fuel or the vehicle population. For instance changes in the regulated diesel sulphur limit.

- The model should be compiled on a Microsoft Excel spreadsheet to facilitate easy dissemination and modification.

The objectives did not include the modelling of costs either to industry or the community as is done by more rigorous models like the IPIECA Toolkit(5).

3. DESIGN OF THE MODEL

It was decided to express gross emissions by mass in tons on a per annum basis. This was derived as follows given that the population has been divided into “n” groups with each arbitrary population group “i” having distinct vehicle characteristics and fuel usage:

If: PR_i = The average rated power of the ith population group
PA_i = The average power output in service of the ith population group
DC_i = The duty cycle factor

$$DC_i = \frac{PA_i}{PR_i} \qquad \text{.....(Eq. 1)}$$

If: H_i = The annual hours of operation of the ith population group
E_i = Representative test data for the ith population group (g/kW/h)
V_i = The number of vehicles in the ith population group
M_i = The annual mileage of the ith population group (km)
TAE = Total annual emissions for the vehicle population (1000 tons / annum)
EF_i = Emission Factor for the ith population group (g/km)

$$TAE = \sum_{1}^{1\ldots n} \frac{(V_i \text{ X } PR_i \text{ X } DC_i \text{ X } E_i \text{ X } H_i)}{1 \text{ X } 10^9} \qquad \text{…..(Eq. 2)}$$

$$EF_i = \frac{(V_i \text{ X } PR_i \text{ X } DC_i \text{ X } E_i \text{ X } H_i)}{M_i} \qquad \text{..…(Eq. 3)}$$

It should be noted that DC_i was taken as being the average duty cycle factor determined from the emissions tests using the European R49 procedure (12) applied in Phase 2 of the VEP and was not determined from real operating cycles in the South African marketplace. This would be a considerable undertaking in its own right. Certainly though the R49 procedure has been based on a representative operating cycle for Europe and if we assume the applicability of the emission data derived from it to our emissions model it is proposed that it is an equally valid assumption to apply the duty cycle factor.

To account for the second objective of the study a more challenging exercise must be undertaken to quantify each of the variables defined for each combination of fuel and engine type. This was attempted by making use of databases external to the experimental work to achieve the following:

- Characterisation of diesel fuel use patterns in South Africa by feedstock, consumer and altitude.

- Characterisation of the diesel engine commercial vehicle population by splitting it into groups that can be matched to the experimental data.

This process is described and linked to the equations above by the flowchart presented in **Figure 1** below. It should be noted from this that the calculation process for light duty commercial vehicles is trivial as the emissions data are expressed in units of grams per kilometer and need only to be multiplied by annual mileage to yield TAE defined above. The accuracy of the model is thus highly dependent on the degree to which the vehicle population can be broken down and matched to appropriate emissions data.

3.1 Characterising the Diesel Fuel Consumption of Commercial Vehicles in South Africa

In order to derive a solution from the model described by Figure 1 the following must be estimated:

- Total fuel consumption. This allows a carbon balance to be performed to check the model result and if necessary proportion the model accordingly.
- The proportion of fuel used at altitude conditions
- The proportion of synthetic fuel used at altitude and sea-level

Two primary resources were applied to the above. The total fuel consumption of the diesel commercial vehicle park alone and the altitude proportion of diesel consumed was calculated from the database of sectorial fuel sales for magisterial districts in South Africa. This is compiled for the oil industry by Caltex, and was made available for this study by the Department of Mineral and Energy Affairs (9). In order to make a regional distinction of what constitutes altitude versus sea-level conditions, these terms had to be defined. The term *sea-level* is of course self explanatory. A useful definition of "*altitude conditions*" for the purposes of modelling would simply be those areas where the reduction in ambient air density is such that the exhaust emissions of a heavy duty diesel engine will deviate significantly from those emitted when operating at sea-level. Topography in the field is however almost infinitely variable so that a model designed according to the this definition would require extensive tests at a variety of altitudes instead of the single site used for the Vehicle Emissions Project. A more practical definition was therefore derived that could be applied to the resources available:

Regions that constitute "altitude conditions" are regions where 91 octane unleaded petrol is sold by fuel vendors.

Fig. 1: Flowchart of Emissions Model for South African Commercial Vehicles

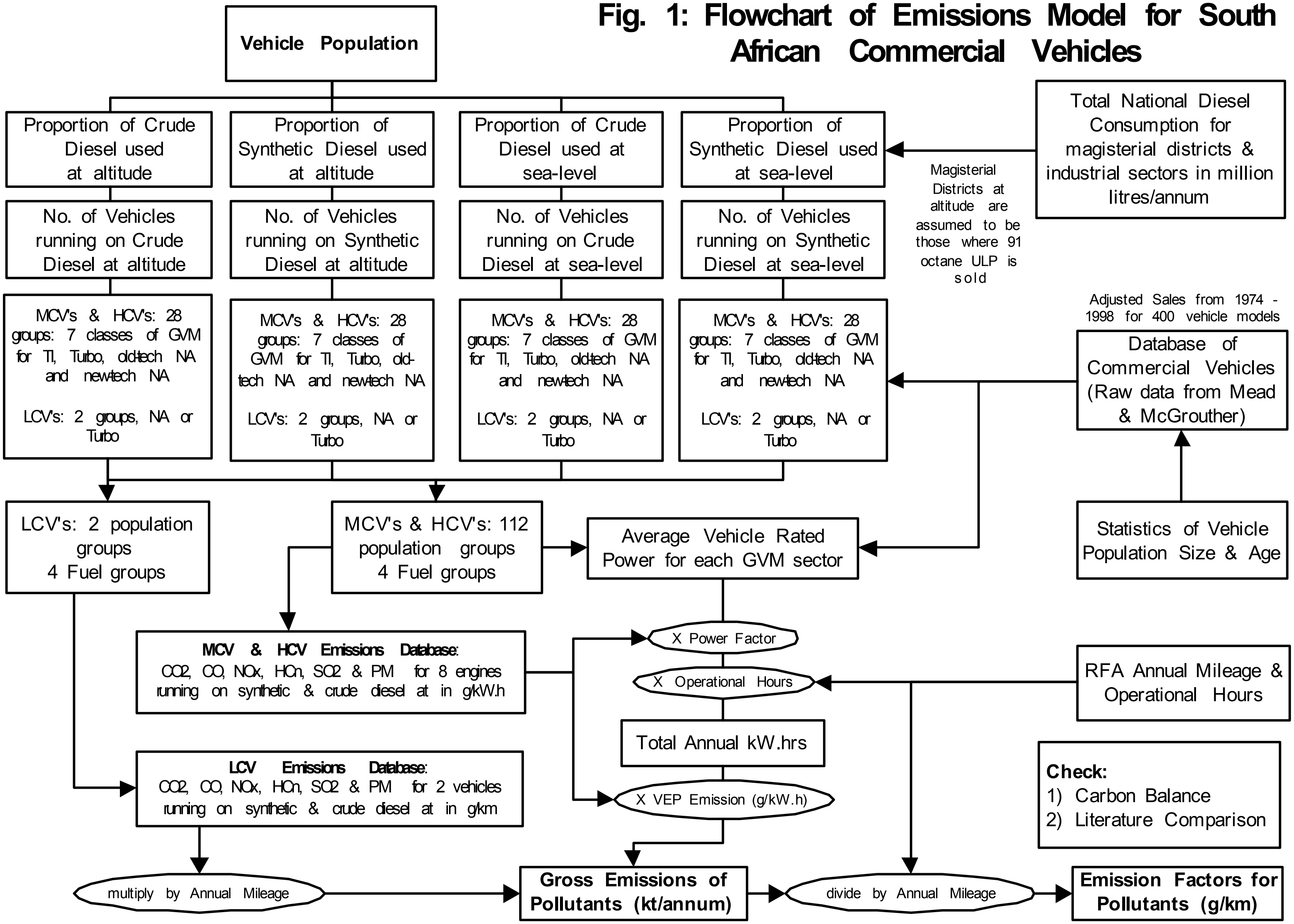


Table 1 below summarises sectorial diesel consumptions, the estimated allocation to commercial vehicles and the estimated altitude consumed proportion by the above definition:

Table 1: Sectorial Breakdown of South African Diesel Consumption [(9)]

Sector	**Sectorial Consumption (litres)**	**Sectorial Consumption (%)**	**Altitude Consumption (litres)**	**Proportion Consumed Altitude (%)**	**Estimated Usage Factor**	**Estimated CV Consumption (litres)**
Road Haulage	9.21E+08	15.4%	6.40E+08	69.5%	1	9.21E+08
Retail Garages	1.38E+09	23.0%	8.43E+08	61.2%	1	1.38E+09
Construction	2.70E+08	4.5%	1.98E+08	73.6%	0.9	2.43E+08
Agricultural Co-ops	3.70E+08	6.2%	2.56E+08	69.3%	0.5	1.85E+08
Pub. Trans. NL Auth.	2.04E+08	3.4%	1.36E+08	66.6%	1	2.04E+08
Government	8.00E+07	1.3%	4.49E+07	56.1%	1	8.00E+07
Farmers	7.43E+08	12.4%	4.79E+08	64.5%	0.5	3.71E+08
Mining	5.22E+08	8.7%	4.38E+08	83.9%	0.7	3.66E+08
Rem. Gen. Trade	6.95E+08	11.6%	4.82E+08	69.3%	1	6.95E+08
Transnet Total	2.28E+08	3.8%	1.39E+08	60.9%	1	2.28E+08
(Trans. Diesel Locos)	1.90E+08	3.2%			-1	-1.90E+08
(Transnet Marine)	1.05E+07	0.2%			-1	-1.05E+07
General dealers	3.72E+08	6.2%	3.01E+08	80.7%	1	3.72E+08
Loc. Mar. Fish	8.57E+07	1.4%	2.88E+06	3.4%	0.5	4.29E+07
Local Authorities	1.06E+08	1.8%	7.79E+07	73.5%	1	1.06E+08
TOTAL	**5.97E+09**	**100.0%**	**4.04E+09**			**4.99E+09**
AVERAGE				**67.6%**		

The proportion of synthetic diesel used was estimated using refinery capacities obtained from the SAPIA yearbook [(25)]. Two assumptions were made, firstly that the Secunda SASOL refinery operates near full capacity for economic reasons and secondly that all production of this refinery is used at altitude conditions and all production of the MOSSGAS refinery is used at sea-level conditions. **Table 2** below presents the estimated breakdown of diesel consumption by refinery and feedstock:

Table 2: Estimated SA Refinery Production of Diesel in Million Litres for 1998 [(25)]

REFINERY	**CAPACITY**	**CAPACITY**	**SOLD IN LOCAL**	**SOLD IN LOCAL**
			INLAND MARKET	**INLAND MARKET**
	(barrels/day)	**(%)**	**(million litres)**	**(%)**
Sapref	180000	27.0%	1480	24.8%
Enref	105000	15.8%	863	14.5%
Calref	100000	15.0%	822	13.8%
Natref	86000	12.9%	707	11.9%
Sasol	150000	22.5%	1718 [(15)]	28.8%
Mossgas	45000	6.8%	370	6.2%
TOTAL	**666000**	**100%**	**5959**	**100%**

Note: Above assumes Local Sales proportional to Capacity except for SASOL which is reported.

The data from **Table 1** and **Table 2** can now be combined to generate the first tier of the model in Figure 1, the proportions of synthetic and crude-derived fuel used by the vehicle population at altitude and sea-level respectively. For example the estimated synthetic consumption at altitude was simply calculated as the product of fuel sold from SASOL in the local inland market from **Table 2** (28.8%) and the average proportion of all diesel consumed at altitude from **Table 1** (67.6%). These proportions and are presented below in **Table 3**. The assumption was made that these proportions equated directly to the proportion of vehicles using these fuels at these conditions and the actual vehicle population was split into the groups shown in **Figure 1** using them:

Table 3: Estimated Proportions for Fuel and Altitude Usage of SA Diesel Commercial Vehicles

Fuel:	**Crude**	**Synthetic**	**Crude**	**Synthetic**
Area:	**Sea-Level**	**Sea-Level**	**Altitude**	**Altitude**
Proportion:	30.4%	2.0%	48.1%	19.5%

3.2 Characterising the Diesel Commercial Vehicle Population

As above, solving the model in **Figure 1** requires certain estimates as follows:

- A proportional breakdown of the vehicle population into established weight categories that can be matched to the data set of engine capacities.
- The breakdown of the naturally aspirated population into old and new technology categories
- The average power of each of the population groups
- The average operating hours and mileage of vehicles in these categories

Published data that accounted for all the above was not found, therefore a database had to be created that related engine characteristics to incidence in the population. The "Commercial Vehicle Data Digest" published by Mead & McGrouther (3,4) was selected as a basis for this database. This source combines the required engine and vehicle data with sales data for most of the models sold in South Africa for the last twenty years with some coverage of the period twenty to thirty five years from the present. Later editions are conveniently compiled in a Microsoft Access Database that reduces the onerous task of large scale manual data entry. The major shortcoming being that at the time of writing the available editions only included data for years of sale up to 1998 which limited the calculation of all results for the entire emissions database to this year.

The primary impediment to applying the Mead & McGrouther database in its raw form to an emissions model is that the total annual sales figures obtained from the digest do not give a proportional representation of a model in the marketplace. It is proposed however that there is a relationship defined by a finite probability of a vehicle being scrapped that increases with every year that passes since the year of sale. This applies especially in the case of large vehicle samples. The relationship between the number of vehicles sold in a particular year and the number of vehicles remaining in the vehicle park in a later year was defined as follows:

If: Y_S = The year of sale
Y_P = The year for which the vehicle park is being characterised
V_P = The number of vehicles in the vehicle park in year Y_P sold in year Y_S
V_S = The number of vehicles sold in year Y_S
$f(Y_P - Y_S)$ = A function that is solved as a "scrapping factor"

$$V_P = f(Y_P - Y_S)\, V_S \qquad \text{…..(Eq. 4)}$$

The scrapping factor function is certainly non-linear as at the very least probabilities of scrapping a vehicle compound for successive years. Accelerated deterioration of the vehicle will further compound an increased rate of scrapping with the passage of time from the year of sale.

Verburgh (29) has proposed scrapping factors for use in modelling the vehicle park for the purposes of assessing what parts should be stocked by manufacturers for historical models. **Figure 2** presents these factors for gasoline passenger vehicles as determined for 1989.

The factors presented in **Figure 2** can be fitted to a curve of the following form:

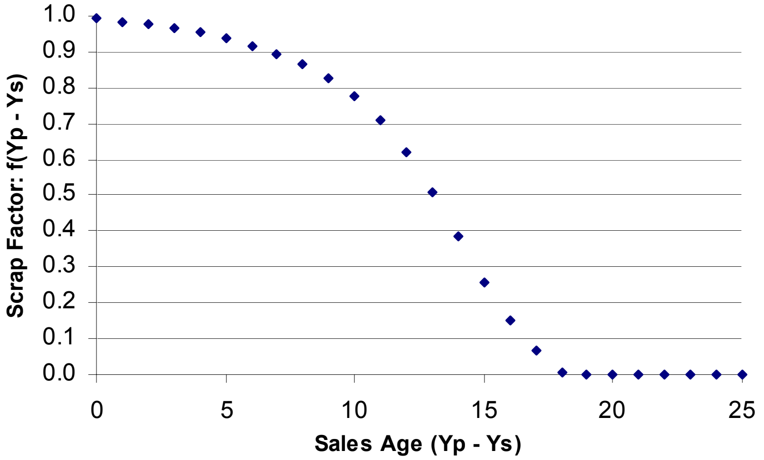
If: A, B, C & D are constants

$$f(Y_P - Y_S) = A(\arctan(B(Y_P - Y_S) + C)) + D \qquad \text{…..(Eq. 5)}$$

Clearly $f(Y_P - Y_S)$ must approach zero as a limit as negative scrapping factors will cause negative populations. This mathematical requirement can be dealt with by defining a final scrapping factor "SF" as follows:

$$SF = \frac{f(Y_P - Y_S) + ABS(f(Y_P - Y_S))}{2} \quad \text{.....(Eq. 6)}$$

Fig. 2: Scrapping Factors for Gasoline Passenger Vehicles as proposed by Verburgh



Sales Age	Scrap Factor	Sales Age	Scrap Factor
0	0.994	10	0.765
1	0.989	11	0.702
2	0.981	12	0.615
3	0.976	13	0.51
4	0.965	14	0.385
5	0.942	15	0.232
6	0.923	16	0.093
7	0.894	17	0.037
8	0.865	18	0.011
9	0.821		

Verburgh's scrapping factors for gasoline vehicles can therefore be defined by the following constants from **Equation 5**:

$A = -0.4496$ $B = 0.2885$ $C = -4.006$ $D = 0.3979$ For an R^2 correlation coefficient of 0.9986

These scrapping factors are likely to be influenced by a number of factors but mainly consumer behaviour, economic pressures and vehicle application. In the case of diesel engines, longer engine life and the commercial application is likely to result in a slower rate of scrapping than that for gasoline passenger vehicles. How then does one determine appropriate scrapping factors with which to relate vehicle sales and actual incidence in the diesel commercial vehicle population?

A solution was proposed whereby **Equation 4** using scrapping factors defined by **Equations 5 and 6** was applied to the NAAMSA total annual sales data (33) for commercial vehicles over a thirty year period. The constants of **Equation 5** were adjusted until a total population was yielded of a quantity that corresponded with available statistics of the number of vehicles on the road and their average age. These characteristics of the estimated population can be defined as follows:

If:
V_T = The total size of the vehicle park in 0th year
$\bar{A}$ = The average age of the vehicle park in 0th year
SF_i = Scrapping Factor for ith year (Equation 6)
V_i = Number of vehicles sold in ith year (NAAMSA)

$$V_T = \sum_{i}^{1\ldots n} SF_i \times V_i \quad \text{.....(Eq. 7)}$$

where SF_n has approached zero

$$\bar{A} = \frac{\sum_{i}^{1\ldots n} SF_i \times V_I \times i}{V_T} \quad \text{.....(Eq. 8)}$$

Statistics of median age were also compared although these are more qualitative as the latest available figures found were for 1989 and had to be extrapolated to the present (6). **Table 4** below lists different sources for total commercial vehicle population, average age and median age (1,6,18,20):

Table 4: Vehicle Park Size & Age Characteristics

Source (at Year end)	Total CV Popl.	M&HCV Popl.	LCV Popl.	Total CV Avg. Age	M&HCV Avg. Age	LCV Avg. Age	Total CV Median Age
CSS (Extrapolated 1998)(6)	1504749			11.8			12.1
AA (1998)(1)	1561207	276977	1284230				
NATIS (1999)(20)	1489283	227468	1261815				
Marketing Shop (1998)(18)	2079819	268156	1811663	9.6	11.9	9.3	
Marketing Shop (2000)(18)	2203172	272061	1931111				

Note: Marketing Shop statistics were supplied with permission by Dave Scott & Associates

Equations 6, 7 and **8** were applied to thirty years of sales figures for light commercial vehicles and combined medium and heavy commercials such that the resulting population was in agreement with data from Reference 18 in **Table 4.** Calculations were for the year 2000, assuming age data was roughly unchanged since 1998. This source was selected in preference to the National Traffic Information System (NATIS) registration based statistics as the figures from Reference 18 are a complete set including both population and age data. Reference 18 is widely used in industry for this type of data. The resulting scrapping factor curves are presented in **Figure 3** below compared to those proposed by Verburgh for gasoline vehicles in 1989 (29). The coefficients, NAAMSA sales data, adjusted sales and resulting population, average age and median age data are presented in **Table 5**. The scrapping factors themselves are not shown but can be easily calculated using the coefficients shown.

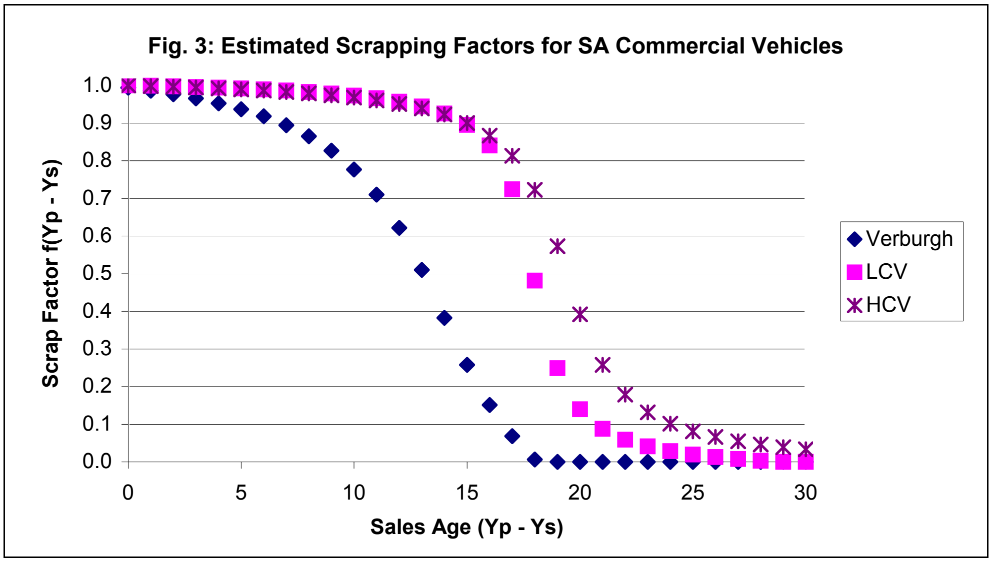
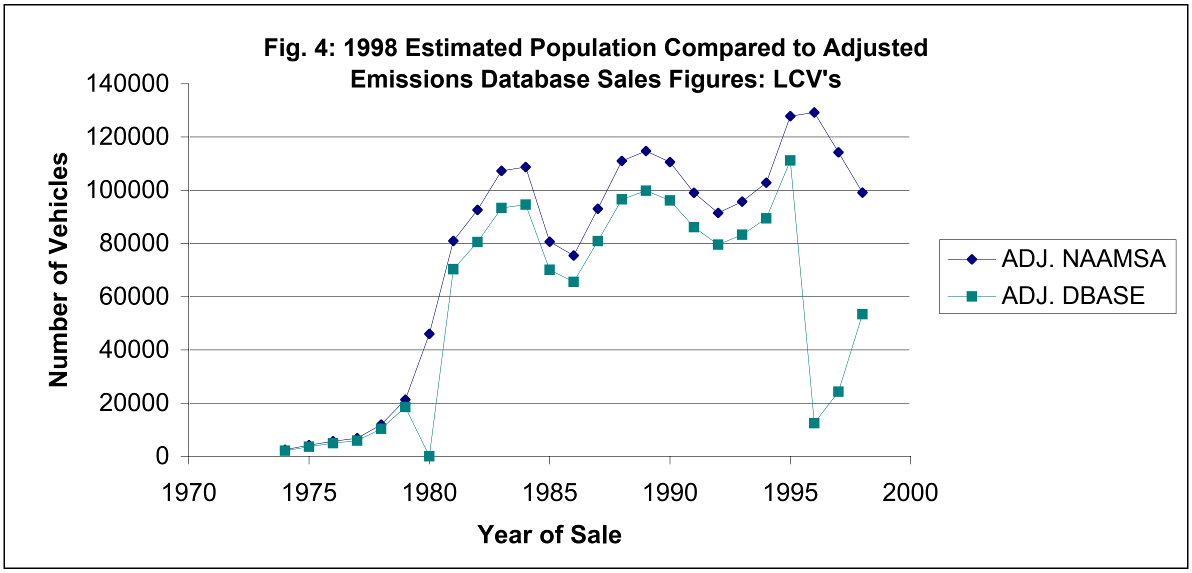


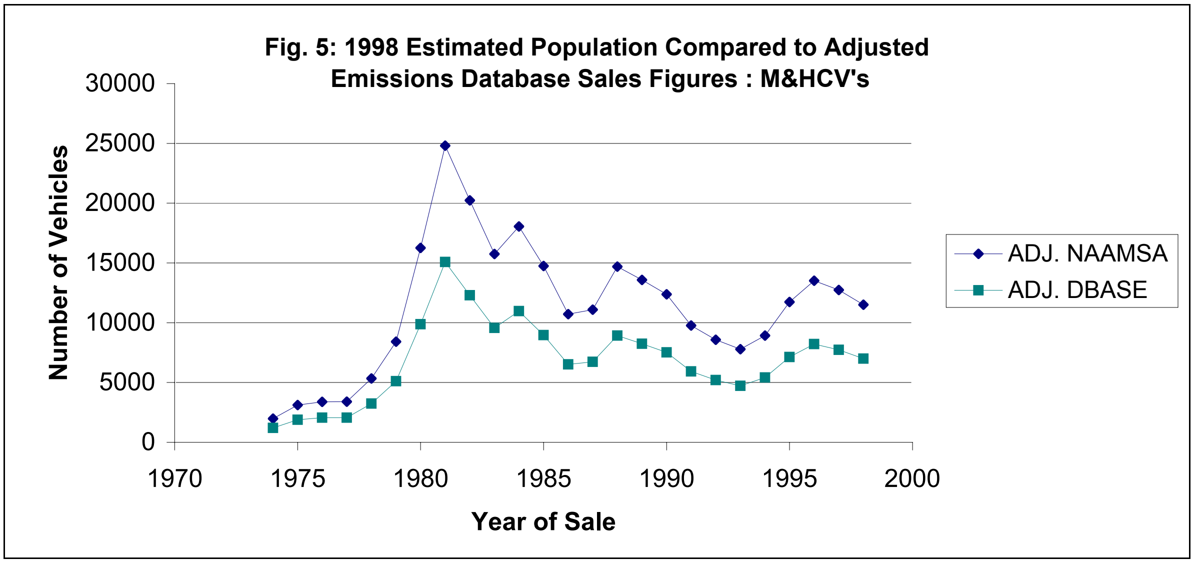
Fig. 3: Estimated Scrapping Factors for SA Commercial Vehicles

Table 5: Characterisation of SA Commercial Vehicle Population using Scrapping Factors (2000)

	Coefficients for Equation 5				Sales (33)	Predicted	Predicted	Predicted
	A	B	C	D	(1970-2000)	Population	Avg. Age	Median Age
LCV	-0.3369	0.8520	-15.30	0.4931	3089128	1931265	9.3	9.07
M&HCV	-0.3356	0.5546	-10.75	0.5041	475977	272066	11.9	12.3

The scrapping factors calculated enabled the proportional adjustment of the Mead & McGrouther database sales to vehicle quantities proportional to actual numbers of vehicles in the population. The characteristics of vehicle mass, power, aspiration etc. will therefore be more proportionally represented in the emissions database. **Figure 4** and **Figure 5** below show the estimated population from each sales year compared to the adjusted vehicle numbers in the emissions database for Light Commercial Vehicles (LCV) and combined Medium and Heavy Commercial Vehicles (M&HCV) respectively.





Database raw sales figures were not increased by more than 20% to conform to a fixed proportion of the population to prevent excessive distortions of certain models. In some cases as can be seen above, under-reporting in the Mead & McGrouther figures was such that it was not practical to smooth the database population and include this point. For example Mead & McGrouther completely omit any sales for light commercial vehicles in 1980.

Other relevant data was listed with each database entry along with the adjusted sales described above. These included power, gross vehicle mass, aspiration, engine type and whether in the case of ADE engines the engine was old or new technology according to the VEP engine sample. Once the numbers sold of each database entry were adjusted to be proportional to the actual vehicle park, this data could be derived as proportions and averages for the entire population. **Table 6** below presents the selected results of this exercise combined with other externally referenced data. Annual mileages were allocated based on vehicle weight using figures published by the Road Freight Association (RFA)(23). The average operating hours were then calculated using assumed average speeds. Lighter vehicles were assumed to have the same average speed as the combined European Urban and Highway light duty emissions cycle(13). The average speed for heavy vehicles was obtained from results of the University of Natal's SIMTRANS computer simulation of long haul truck trips(28). The RFA figures are derived from a cost calculation for new vehicles and do not necessarily hold for vehicles over the entire thirty year age span of the emissions model. Indeed use of this data in its raw form yielded results with excessive carbon output relative to the known fuel consumption from SAPIA. The RFA mileages were therefore multiplied by a factor factor of 0.832 such that the model carbon and SAPIA consumption balanced.

Table 6: Selected Estimated Diesel CV Park Characteristics from Emissions Model

LCV GVM (kg)	Avg. Pwr (kW)	Turbo Frac. (%)		Total No. of LCV	Average Speed (km/hr)	Annual Mile. (R) (km)	Annual Service (hrs)	Diesel LCV (%)	No. of Diesel LCV	Park Cap. (GW)	Energy Cap. (TW.h)
LCV < 3500	55.8	14.0%		1811663	46.5(R)	30000	645	20.9%	377964	21.09	13.61

M&HCV GVM (kg)	Avg. Pwr (kW)	Turbo Frac. (%)	TI Engines (%)	% ADE Engines (%)	Average V. Speed (km/hr)	Annual Mile. (R) (km)	Annual Service (hrs)	Popl. Fraction (%)	No. of Vehicles	Park Cap. (GW)	Energy Cap. (TW.h)
3501-7500	68	8.0%	7.8%	74.7%	46.5(R)	39909	858.3	19.8%	53184	3.6	3.1
7501-10 000	89	2.7%	0.0%	56.6%	46.5(R)	39909	858.3	10.7%	28804	2.6	2.2
10 001-12 500	95	0.0%	0.0%	72.4%	46.5(R)	39909	858.3	18.4%	49456	4.7	4.0
12 501-15 000	106	39.6%	0.4%	76.0%	46.5(R)	38662	831.4	24.4%	65398	6.9	5.8
15 001-17 500	161	42.5%	3.5%	51.6%	46.5(R)	51718	1112.2	4.4%	11768	1.9	2.1
7 501-20000	202	55.6%	4.8%	98.8%	56.0	63527	1134.4	2.4%	6448	1.3	1.5
Over 20 000	231	57.5%	14.5%	58.6%	65.5(R)	87145	1331.5	19.8%	53097	12.3	16.3
AVERAGE	**124**	**26.1%**	**4.8%**	**69.0%**	**50.5**	**50074**	**963**				
TOTAL								**100.0%**	**268155**	**33.3**	**35.1**
PARK AVG.	**84**				**48**	**38331**	**777**				
PARK TOT.									**646119**	**54.4**	**48.7**

Note: *Annual mileages have been proportioned relative to RFA figures (23) but factored so that carbon is balanced.*

The above figures were used directly in the calculation of Total Annual Emissions as described by the model depicted in **Figure 1** above.

3.3 Scenario Modelling

A number of scenarios were modelled by adjusting the engine emission data input to the model. These were as follows:

3.3.1 No Synthetic Fuel Industry

This scenario was modelled by simply substituting the emission data for crude-derived fuel into the data fields formerly containing the synthetic fuel emission data for altitude and sea-level conditions respectively. A formula toggle was programmed in the spreadsheet model so that cutting and pasting operations were unnecessary.

3.3.2 The Conversion of all MCV's and HCV's to Turbo-intercooled Engines

Proportions of vehicles allocated to the different types of engine aspiration as presented in **Table 6** were all changed to reflect a 100% turbo-intercooled population. This was only applied to Medium and Heavy Commercial Vehicles as no turbo-intercooled data was available for Light Commercial Vehicles. The vehicle population was kept the same for this exercise but clearly the increased capacity of the vehicle park will require less trips to transport the same freight. Therefore the operating hours were adjusted so that the MCV and HCV "Energy Capacity" shown in **Table 6** was the same as the baseline (48.7 TeraWatt.hours). This is simply the product of the park capacity (gW) and the annual operating hours and represents the vehicle park energy output assuming constant operation at rated conditions. Thus the scenario and the baseline are compared assuming the same annual output given that duty cycle factors (**Equation 1**) remain constant for both.

3.3.3 The Conversion of all Naturally Aspirated MCV's and HCV's to Turbocharged Engines

The methodology for modelling this scenario was identical that for turbo-intercooled conversion described above in **Section 3.3.2**. Although turbo-charged data was available for Light Commercials they were not included so that the results would be comparative to the turbo-intercooled conversion scenario.

3.3.4 *The Provision of the Medium and Heavy Commercial Capacity by Vehicles Greater than 20 000 kg GVM*

The objective of this scenario was to simulate the effect of using only large vehicles to meet the country's goods transport needs. In other words transport the annual commercial road freight of the country in larger loads on larger vehicles with fewer total trips. In this case the total population was reduced to take account for the very much larger power per vehicle of the 20 000+ kg Gross Vehicle Mass class. Simply put, 144 017 of these vehicles have approximately the same capacity as the Medium and Heavy Commercial population of the baseline model shown in **Table 6** above (33.3 GW). Annual Vehicle operational hours were again reduced as described in **Section 3.3.2** so that the estimated annual energy output was the same as the baseline model.

3.3.5 *The Reduction of the Regulated Limit for Diesel Fuel Sulphur Level*

Five scenarios were modelled to estimate the effect on commercial vehicle emissions of reducing the regulated diesel fuel sulphur limit of 0.55% down to 0.3%,0.2%,0.1%,0.05% and 0.005%. Diesel fuel sulphur level has a direct and quantifiable effect on particulate matter (PM) and sulphur dioxide (SO_2) emissions.

In the case of SO_2, emissions were assumed to be directly proportional to fuel sulphur by a linear relationship through the origin. Thus the test data for SO_2 was simply adjusted by interpolating linearly for the fuel sulphur level being evaluated between the fuel sulphur level of the test fuel and zero. That is to say, for zero fuel sulphur the interpolation will return a value of zero SO_2.

The relationship between fuel sulphur level and PM is well researched. Good agreement was found between three different sources (21,31,34). These are presented below in **Equations 9**, **10** and **11:**

If: ΔPM = The change in particulate matter emissions (g/kW.h)
ΔS = The change in fuel sulphur content (0.1 % weight)

ACEA propose in the World Wide Fuel Charter (31):

$$\Delta PM = 2.553 \times 10^{-2} \Delta S \quad \text{for bsfc} = 200 \text{ g/kW.h} \quad \text{.....(Eq. 9.1)}$$

$$\Delta PM = 1.809 \times 10^{-2} \Delta S \quad \text{for bsfc} = 270 \text{ g/kW.h} \quad \text{.....(Eq. 9.2)}$$

Barry et al propose in Owen & Coley (21):

$$\Delta PM = 2.282 \times 10^{-2} \Delta S \quad \text{.....(Eq. 10)}$$

Zelenka et al (34) propose:

$$\Delta PM = (2.685 \times 10^{-2} \pm 0.537 \times 10^{-2}) \Delta S \quad \text{.....(Eq. 11)}$$

It was decided to apply **Equation 11** only to the model as **Equations 9.1** and **9.2** were derived for a maximum fuel sulphur level of only 0.05% while the model covers a range an order of magnitude greater. **Equation 11** is more recent research than **Equation 10** and is derived from a larger data set.

3.3.6 *A Regulation Compliant Vehicle Park (Euro 1 –3)*

This scenario modelled the effect of importing European regulation compliant vehicles. Three tiers of regulation were assessed, the so-called Euro 1, 2 and 3 limits (12,13) for both heavy-duty commercials (load specific limits in g/kW.h) and light commercials (distance specific emissions in g/km). A formula toggle in the model allowed the test data from the baseline model to be simply substituted with the limit values but only if smaller than the test data.

It is of course true that vehicle ageing effects are not taken into account with any comparison of these scenarios with the baseline. It was assumed though that similar ageing effects would influence the population once compliant vehicles have replaced the current population and that a relative comparison (percentage difference) taking no account of ageing is thus approximately valid.

3.3.7 Conversion of the Vehicle Park to Compressed Natural Gas (CNG) Fuelled Engines

This scenario was viewed as of great strategic importance in the light of the rapid growth of the Natural Gas industry in South Africa (32) and the growth in gas vehicle conversion in general although this has been mostly light duty conversions to Liquid Petroleum Gas (LPG). LPG is an oil refining by-product that is mostly pentane and butane. A current surplus and low retail price has made it an attractive fuel for captive fleets. CNG has however become the fuel of choice for heavy duty gas applications globally. Heavy duty gas engines are manufactured from diesel engine parts off the assembly line for reasons of economy. The octane rating of CNG (±120) therefore requires less reduction of the original engine compression ratio than LPG (octane rating 90 – 100) as well as allowing for higher thermal efficiency (17).

The data set used to model this scenario was not rigorous and was generated from data for only one engine reported by MAN for their 11.97 litre natural gas engine (17). This is the exact displacement of the 4-series ADE engines tested for the VEP emissions data set used to calculate the baseline. The 4-series engines represent larger engine displacements in the VEP data. ADE 3-series engines accounted for the smaller engine displacement sample. The MAN data were also determined using the European R49 test cycle and are presented below in **Table 7**. NOx and PM emissions are very low relative to diesel engines:

Table 7: Emissions Data for Heavy-Duty MAN CNG Engine(17)

HCn (g/kW.h)	CO (g/kW.h)	NOx (g/kW.h)	PM (g/kW.h)
0.50	1.00	1.00	0.02

CO_2 emissions were estimated using a figure of 35% efficiency loss observed by MAN relative to diesel for CNG engines. Estimated data was generated for 3-series engines, light commercials and altitude conditions for all engine categories by simply adjusting the MAN data in proportion to the average differences between engines and fuels in the original VEP data set. The altitude effect and the engine displacement effect on emissions were therefore modelled as being the same as for the baseline model.

4. EMISSIONS MODELLING RESULTS

4.1 Baseline Results

Initially a baseline was calculated to estimate the 1998 Emission Factors and Total Annual Emissions and. These figures are presented below in **Table 8** and **Table 9**.

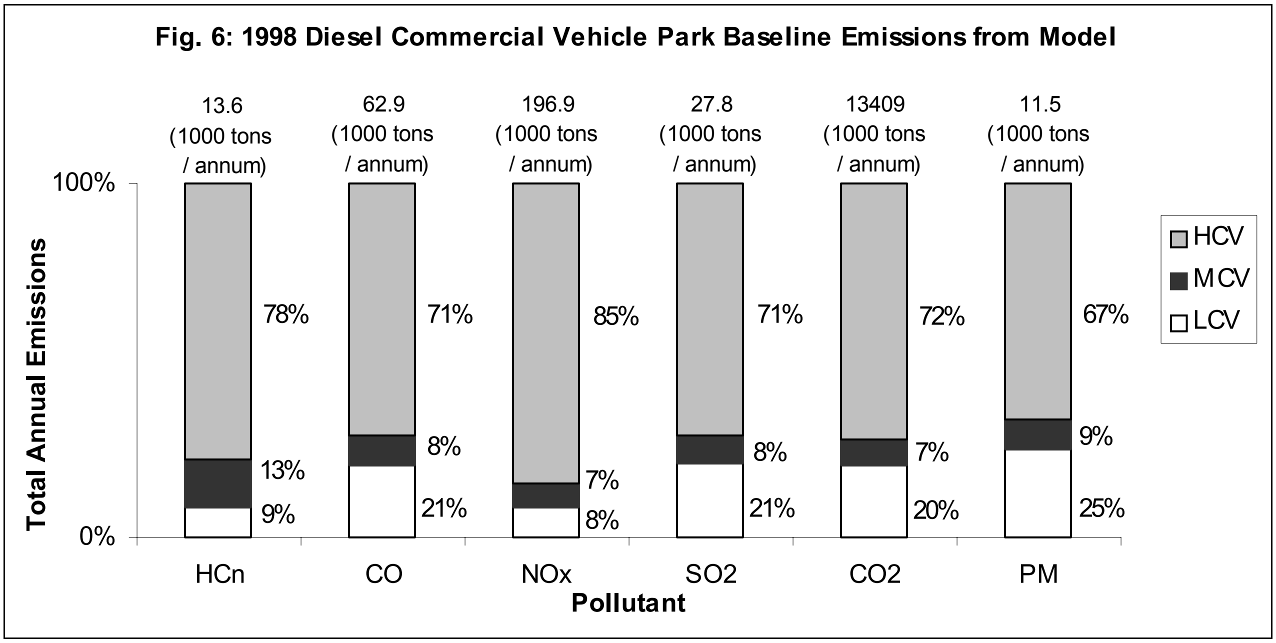
Table 8: Estimated Emission Factors for Diesel Commercial Vehicles (1998)

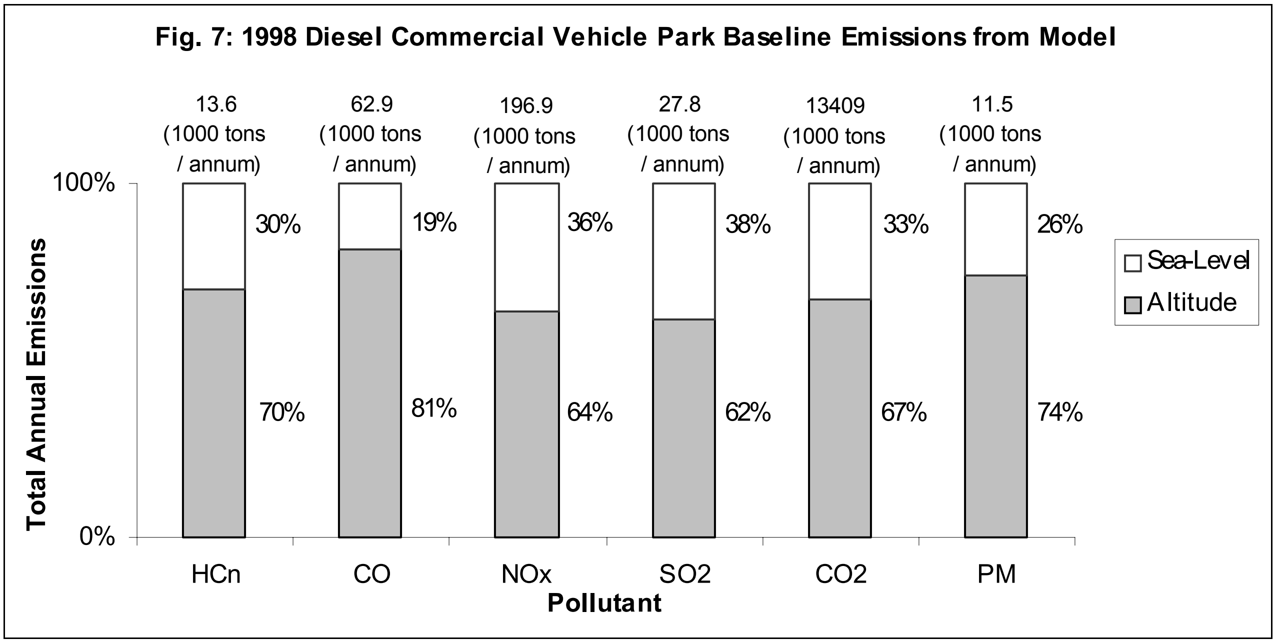
Vehicle	Emission Factors (g/km)					
Type	HCn	CO	NOx	SO2	CO2	PM
LCV	0.10	1.14	1.47	0.51	237	0.25
MCV	0.86	2.41	6.18	1.02	473	0.47
HCV	1.05	3.82	13.04	1.66	805	0.68
M&HCV	1.01	3.54	11.68	1.54	739	0.64
All CV's	0.48	2.14	5.70	0.94	446	0.41

Table 9: Estimated Total Annual Emissions for Diesel Commercial Vehicles (1998)

Vehicle	Total Annual Emissions (thousand tons/annum)					
Type	HCn	CO	NOx	SO2	CO2	PM
LCV	1.17	12.92	16.61	5.81	2691	2.84
MCV	1.82	5.12	13.12	2.17	1004	1.01
HCV	10.58	44.86	167.15	19.86	9714	7.70
M&HCV	12.40	49.98	180.27	22.03	10719	8.71
All CV's	13.57	62.90	196.88	27.84	13409	11.55

Figure 6 and **Figure 7** below show the breakdown of emissions according to vehicle type and altitude respectively:





4.2 Scenario Modelling Results

The results of the scenario modelling exercise are presented graphically below in **Figures 8 – 13** Each pollutant HC_n, CO, NO_x, PM, SO_2 and CO_2 is plotted respectively against the baseline result.

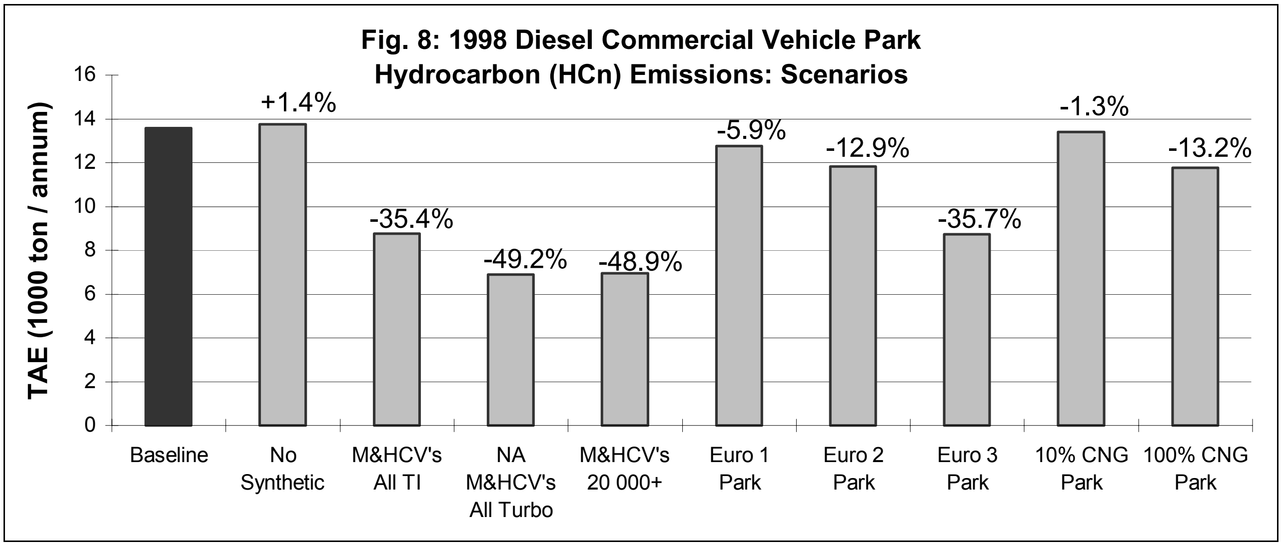


Fig. 8: 1998 Diesel Commercial Vehicle Park Hydrocarbon (HCn) Emissions: Scenarios

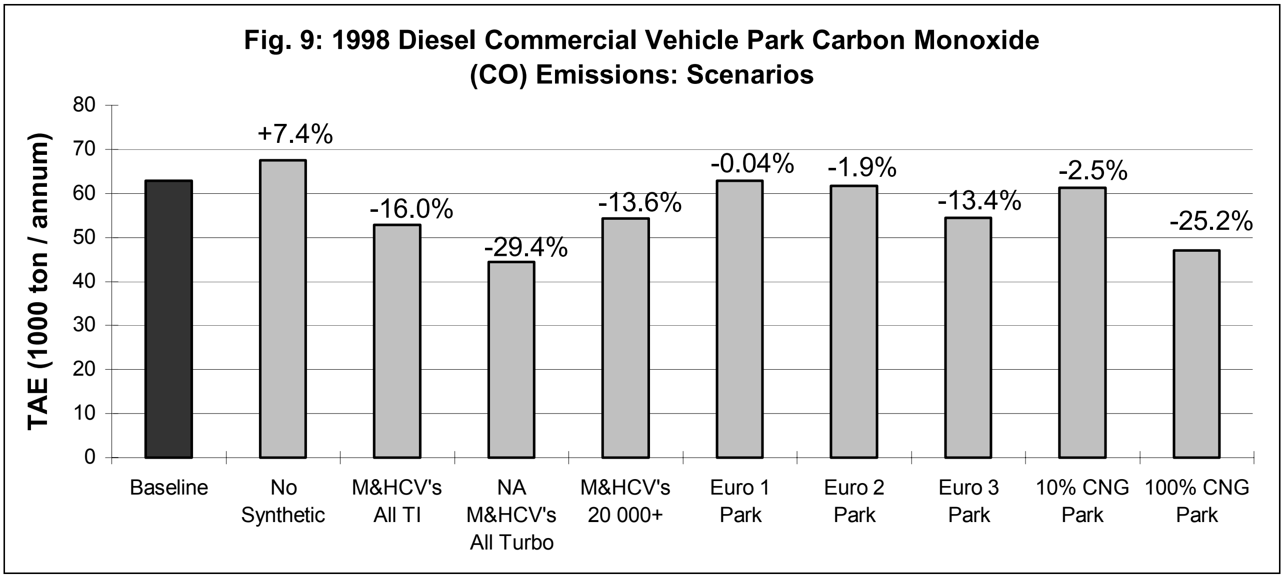


Fig. 9: 1998 Diesel Commercial Vehicle Park Carbon Monoxide (CO) Emissions: Scenarios

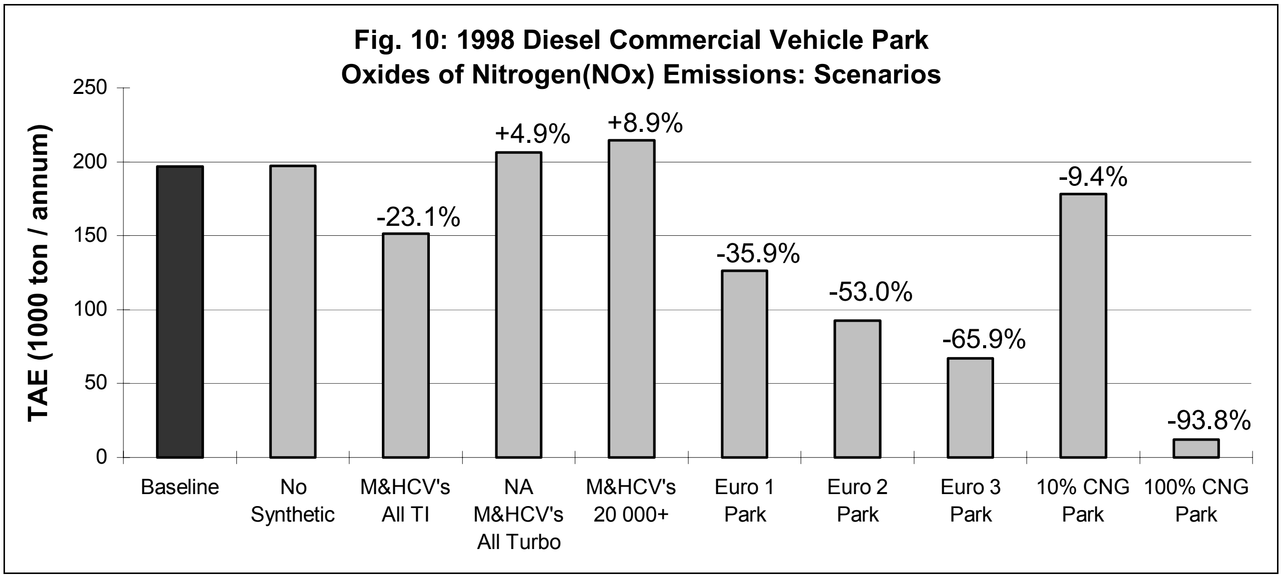


Fig. 10: 1998 Diesel Commercial Vehicle Park Oxides of Nitrogen(NOx) Emissions: Scenarios

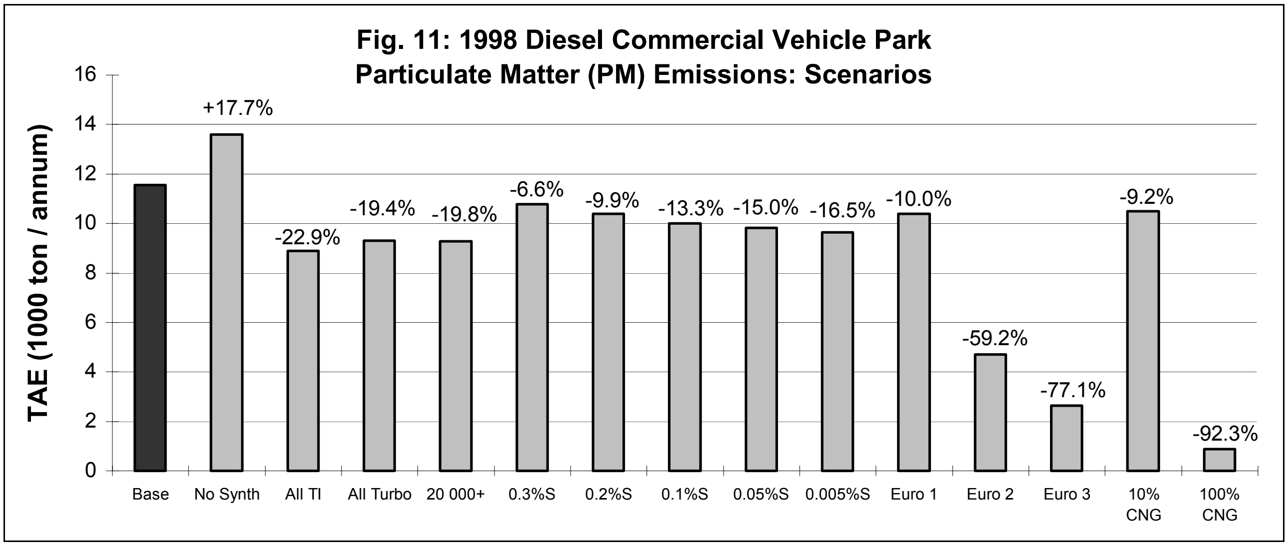


Fig. 11: 1998 Diesel Commercial Vehicle Park Particulate Matter (PM) Emissions: Scenarios

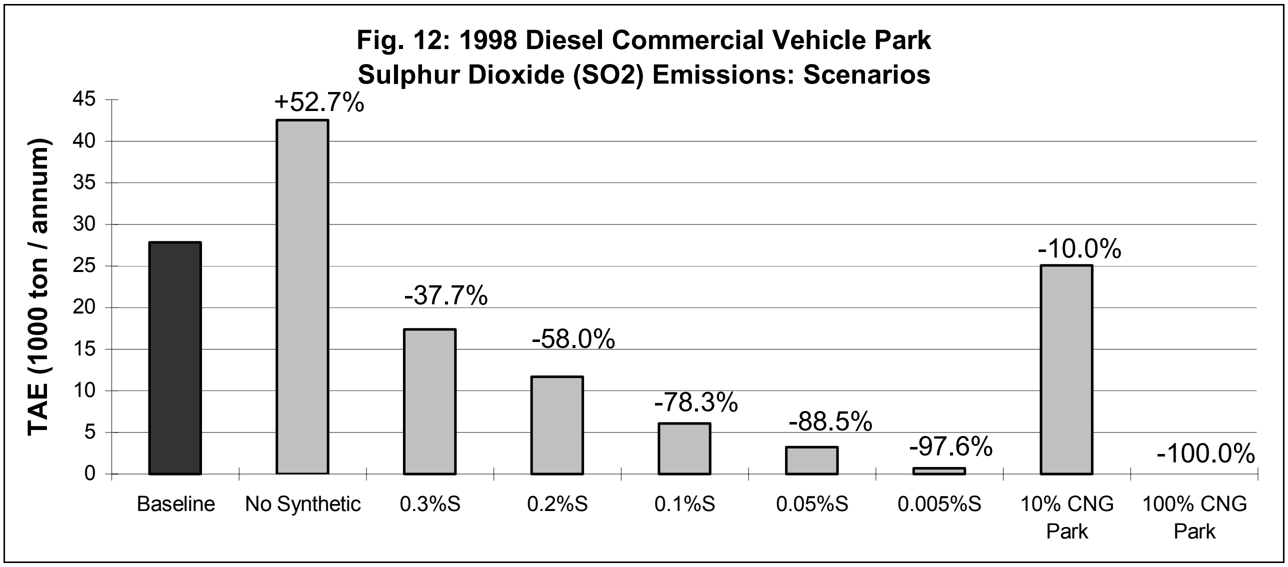


Fig. 12: 1998 Diesel Commercial Vehicle Park Sulphur Dioxide (SO2) Emissions: Scenarios

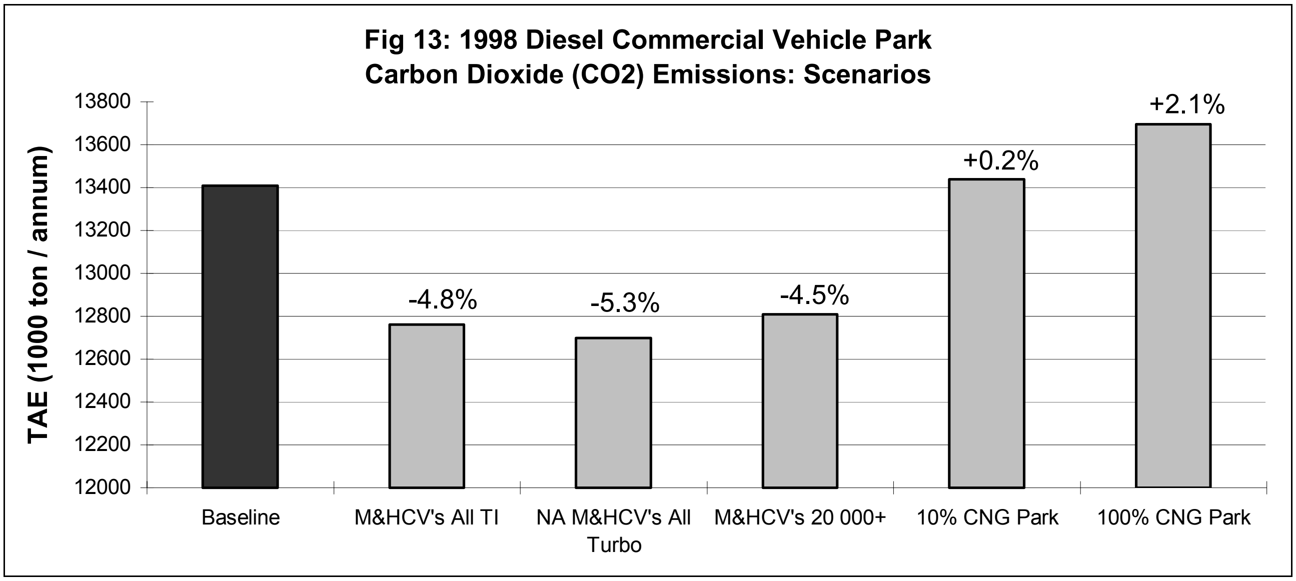


Fig 13: 1998 Diesel Commercial Vehicle Park Carbon Dioxide (CO2) Emissions: Scenarios

5. DISCUSSION

5.1 Discussion of the Scenario Modelling

5.1.1 Effect of the Synthetic Fuel Industry

South Africa is an acknowledged world leader in this industry. Currently this has a very emissions positive effect primarily due to the very low sulphur levels of synthetic fuels. Although this effect will diminish with reduced crude-derived sulphur levels, the synthetic industry has made further strides in the provision of special low emission diesel fuels, for example SASOL's Slurry Phase Distillate an ultra-high cetane fuel that offers significantly lower emissions even relative to European low emission diesels (2,24).

5.1.2 Engine Type Variation

Turbocharging is clearly the most certain route for reducing commercial vehicle emissions as there is the added incentive of reduced running costs. The high proportion of activity at altitude conditions makes turbocharging a particularly effective measure for emissions reduction. Intercooling is however essential to prevent NO_x penalties.

5.1.3 Vehicle Size

Larger diesel engines are more efficient due to a lower surface area to volume ratio and lower friction due to lower running speeds. While light vehicles are convenient for the consumer they are not desirable from an environmental or fuel economy perspective, although in the case of NO_x emissions the model shows penalties for large vehicle use. Clearly though the economic necessity for South Africa to create a small and medium business focussed economy will tend to drive the continued popularity of light commercial vehicles. Consumer behaviour could perhaps be modified in cities like Cape Town by fostering urban delivery subcontractors that use larger vehicles and serve many businesses. The practicality of this and costs to the ratepayer of damage to the roads has to be carefully evaluated though.

5.1.4 Fuel Sulphur Level

The direct relation between fuel sulphur and particulate matter and sulphur dioxide emissions results in a continuing reduction as fuel sulphur is reduced. This is particularly the case for SO_2 which although not regulated due to its purely fuel derived nature is a serious threat to human health (8). Particulate reductions are significant but not large. Therefore one must carefully balance the very high costs of sulphur reduction with the emissions gains. Molden (19) has estimated the cost of reducing diesel sulphur from the new limit of 3000 ppm to an even lower 500 ppm at R3 billion. Of concern are also refinery emissions themselves particularly CO_2 emissions which can be expected to increase sharply (7,14). Ultimately fuel sulphur reduction is likely to be determined not by emissions impact but by the minimum requirements of engines currently being imported.

5.1.5 Regulation Compliance

The results show that given good vehicle park maintenance and lower fuel sulphur (0.2%) that the South African commercial vehicle park should approach the equivalent of Euro 1 emissions compliance at present. It should be borne in mind however that the age effect on the baseline emissions would in all probability be very profound if it could be modelled although this can be balanced against the fact that new engines being imported have emissions far lower than Euro 1 levels. In contrast Euro 2 and Euro 3 compliance imply very extensive changes to the vehicle population. Given the characteristics of the population discussed in this study, this will require at least a decade of selective importing of engines and vehicles meeting these standards. Certainly significant improvements in air quality can be expected given that these engines are operated at the emission regulation fuelling strategies and with exhaust treatment devices like particulate traps fully functional. The temptation in the kiloWatt hungry South African market is to alter fuelling strategies to appeal to consumers that regularly overload vehicles for short term economic returns. Disabling or omitting exhaust aftertreatment devices might also be used by distributors and CKD assemblers to firm up small profit margins in depressed markets.

5.1.6 CNG / LPG Conversion

This is probably the best medium term measure to reduce emissions of particulates, oxides of nitrogen and sulphur dioxide especially in urban environments. Although thermal efficiency is lower than for compression ignition engines running on diesel, CNG is a low carbon fuel so CO_2 penalties are marginal as shown in **Figure 13**. The supply of CNG to Sasolburg and the mooted pipeline from the Kudu Gas fields to Cape Town could drive a rapid development of a vehicle gas industry. Given the capacity of the commercial vehicle population estimated by this paper at some 55 GW or the equivalent of 14 large highveld coal fired power stations, potential gains for fuel suppliers are great even given a duty cycle of only 30% and limited market penetration. Fuelling a large percentage of new vehicles on CNG will slow up the demand for increased refinery capacity for diesel while allowing oil companies to diversify into a new energy source market. The state has openly stated it's interest in offering incentives and it is to be hoped that this far sighted approach is matched by industry (32).

5.2 Weaknesses of the Model

The model has definite shortcomings that in most cases can be improved upon. These can be summarised as follows:

- The emission data set does not take account of ageing effects on vehicle emissions. Vehicle emissions can be assumed to deteriorate seriously with age particularly if maintenance is poor.

- The emissions data set does not take account of new technology entering the marketplace, specifically electronic control, common rail injection and variable geometry turbo-charging. The emissions data consists of measurements from ADE engines only and while this may be representative of 1998, the year of calculation for this study for which an ADE content of 69% was calculated, the incidence of ADE engines in the population will already be much diluted by new engines. It should be stressed that using the regulated emissions limits from the country of origin for imported engines is not a solution as the actual emissions are often far lower especially in the case of unburned hydrocarbon and carbon monoxide emissions. Furthermore this does not take local fuel effects into account.

- The Mead & McGrouther vehicle database has a highly suitable format and concept for the purpose of vehicle park modelling but sales data is partial and the published database is updated slowly, the latest figures at the time of writing being for 1998. Certain engine data is missing for some models which requires great effort to make estimates or corrections

- The VEP emissions data for diesel light commercial vehicles is very limited and highly unrepresentative of technology. For instance the turbocharged vehicle model tested had higher particulate emissions than the naturally aspirated vehicle.

- The adjustment of average vehicle mileages by carbon balance is assumed and needs to be verified by more accurate data from the field if baseline accuracy is required. For comparative purposes however this is probably not necessary.

- The turbo-intercooled data available is insufficient to evaluate this technology. This is especially true for LCV's where no data was available.

- No data is available for diesel passenger cars that are an increasing presence in the marketplace and should be included either in a passenger car database or with the commercial vehicles in a diesel fuel specific database. Rayner(R) has predicted a sustained increase in the proportion of diesel passenger cars and measures will have to be taken to take account of their emissions.

Since the time of Phase 2 of the VEP program, considerable world class emissions testing infrastructure has developed in South Africa, specifically at the Eurotype test centre in East London, the VW South Africa emissions test facility in Port Elizabeth and the SASOL Oil test facility in Sasolburg. There is no reason why the data availability shortcomings described above cannot be resolved by a sustained and continually updated program that obtains data from all or either of these facilities. Certainly regular testing offers an improved economy of scale and ensures that expertise and equipment is maintained which unfortunately was not the case with the VEP contractors.

6. CONCLUSIONS

- A simple bulk emissions model of the vehicle population is a useful tool for estimating the impact of fuel and technology changes on air quality.

- The vehicle park and fuel supply chain can be adequately modelled using available databases at low cost. Improvements to the vehicle park database should however be encouraged.

- Engine emission data for South African commercial vehicles is outdated and limited in model coverage. Testing should be routine to maintain economic testing volumes and thus sustain measurement quality.

- A healthy synthetic fuel industry and reduced crude-derived fuel sulphur will have a very positive effect on air quality as regards emissions of particulates (PM) and sulphur dioxide (SO_2). The primary gain for particulate emission reductions with reduced fuel sulphur will be through the enabling of exhaust after-treatment technology like particulate traps which are not currently fuel sulphur tolerant(15).

- New engine technologies should improve air quality substantially. Naturally aspirated diesel engines are not positive from an emissions perspective especially given the considerable economic activity at high altitude.

- Small business growth and a concommitant growth in light commercial vehicles will impact air quality negatively. Efforts to optimise the emissions of these vehicles should be undertaken.

- The importation of Euro 2 and Euro 3 compliant vehicles will have a highly significant impact on air quality. Regulatory bodies need to ensure that these engines are sold into the market operating as designed.

- Local manufacturers and distributors should be encouraged to begin gas vehicle demonstrator projects to raise consumer awareness and begin negotiation of such vehicles from parent companies at an affordable cost. Government needs to finalise and guarantee incentive schemes to promote the use of CNG and LPG. Efforts should be made to incorporate vehicles as a significant consumer of the Kudu Gas pipeline to assist in justifying the economics of installation.

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8. ANNEXURE 1

Abbreviations used in the text can be defined as follows:

CKD:	Complete Knock Down Assembly (of vehicles)
CNG:	Compressed Natural Gas (80 – 98% methane)
CO:	Carbon Monoxide (a gaseous exhaust emission)
CO_2:	Carbon Dioxide (a gaseous exhaust emission)
Euro1:	European vehicle emissions legislation limits from 1994
Euro2:	European vehicle emissions legislation limits from 1997
Euro3:	European vehicle emissions legislation limits from 2001
GVM:	Gross Vehicle Mass
HC_n:	Unburned Hydrocarbons (a gaseous exhaust emission)
HCV:	Heavy Commercial Vehicle ie: Gross Vehicle Mass > 7501 kg
LCV:	Light Commercial Vehicle ie: Gross Vehicle Mass < 3500 kg
M&HCV:	Medium and Heavy Commercial vehicles combined
MCV:	Medium Commercial Vehicle ie: 3500 kg < Gross Vehicle Mass < 7500 kg
NO_x:	Oxides of Nitrogen (a gaseous exhaust emission)
PM:	Particulate Matter (a solid carbonaceous exhaust emission of small breathable particles)
SO_2:	Sulphur Dioxide (a gaseous exhaust emission)
TAE:	Total Annual Emissions (1000 ton/annum)
VEP:	Vehicle Emissions Project