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Effects of driving cycle on CO_2 emission of heavy-duty commercial vehicles based on VECTO simulation

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Abstract: European has adopted Vehicle Energy Consumption Calculation Tool (VECTO) to calculate the fuel consumption of heavy-duty commercial vehicles for fulfill the carbon-neutral requirement. In this paper, VECTO was used to evaluate the CO_2 emission for four types of vehicles including city bus, coach, heavy truck and trailer tractor. China Version World Transient Vehicle Cycle (C-WTVC) and China Heavy-duty Commercial Vehicle Test Cycle (CHTC) were used as simulation cycles. The CO_2 emission characteristics and cycle differences of both cycles were compared and analyzed. The results show that CO_2 emissions of CHTC are higher than that of C-WTVC for these four types of vehicles with increase percentages ranging from 1.5% to 19%. Cycle average acceleration difference is the most predominant factor. Driving strategy changes due to the cycle difference also lead to the CO2 emission difference because the engine operation points has changed to some extent.

1. Introduction

CO2 is a a representative greenhouse gas which mostly sourced by fossil fuel consumption. Due to the high fuel consumption for per heavy-duty commercial vehicle, the CO2 emission have always been the focus of automobile energy saving and air pollution prevention [1-2]. Trucks, buses and coaches currently produce about a quarter of carbon dioxide (CO2) emissions from road transport in the European Union (EU) and some 5% of the EU's total greenhouse gas (GHG) emissions [3]. In order to reduce the CO2 emissions from vehicles and fulfill the carbon-neutral requirements, EU has adopted Vehicle Energy Consumption Calculation Tool (VECTO) to calculate the fuel consumption of heavy-duty commercial vehicles [4-6]. While China is also upgrading the fuel consumption standard from Phase 3 to Phase 4[7]. A major change besides the fuel consumption limitation is that the test cycle will changed from China Version World Transient Vehicle Cycle (C-WTVC) to China Heavy-duty Commercial Vehicle Test Cycle (CHTC) [8-9] .

Because China requires to use chassis dynamometer to measure the fuel consumption of heavy-duty vehicle, it is seldom use simulation tool to calculation fuel consumption. In this context, this paper introduces the simulation calculation process of the VECTO software in detail, and compares the differences between CWTVC and CHTC. Then VECTO was used to evaluate the CO2 emission for four types of vehicles including city bus, coach, heavy truck and trailer tractor under both cycles.

2. VECTO simulation setup

2.1 VECTO introduction

VECTO calculates the fuel consumption of heavy-duty commercial vehicles by combining the component test and vehicle simulation.The component test mainly includes engine test, transmission system test, gearbox test, reducer test, air drag test and tire test. The test data needs to be processed into the corresponding format data file before it can be input into VECTO software for the calculation of fuel consumption. The vehicle simulation need to input the vehicle, engine and gearbox parameters into corresponding module to get the data files in the required format. Then, the above data files and test cycles files are input into the job file module to get the data file for fuel consumption calculation. After calculation, the transient and final fuel consumption results under test cycles are obtained. The CO2 emission can be calculated by a fixed factor as shown in Table 1 for different fuels.

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Table 1 Fuel consumption and CO2 emission conversion factor

Engine Fuel type	Reference Fuel	Density	CO2 content	Lower heating value
	-	kg/m3	g_CO2/g_Fuel	MJ/kg
Diesel/CI	B7	836	3.13	42.7
Ethanol/CI	ED95	820	1.83	25.7
Petrol/PI	E10	750	3.04	41.5
Ethanol/PI	E85	786	2.09	29.1
LPG/PI	LPG	Not required	3.02	46
NG/PI	G25	Not required -	2.54	45.1

2.2 Vehicle specifications

Four different types of heavy-duty commercial vehicles, including city bus, coach, heavy-duty truck and trailer tractor, are selected as prototype vehicles. The main parameters of the vehicles are shown in Table 2.

Table 2 Main parameters of simulation vehicles

Parameter	**Vehicle No.1**	**Vehicle No.2**	**Vehicle No.3**	**Vehicle No.4**
Type	City bus	Coach	Heavy-duty truck	Trailer tractor
Total mass	11990kg	25000kg	7495kg	35000kg
Curb mass	4670kg	14800kg	4300kg	8200kg
Engine idle speed	600rpm	600rpm	750rpm	600rpm
Engine rated speed	2200rpm	1740rpm	2200rpm	1740rpm
Engine rated power	175kw	250kw	115kw	325kw
Engine displacement	6.871L	7.7L	2.78L	12.74L
Gear number	6	6	6	12
Rear axle ratio	6.2	4.9	4.33	2.64
Gearbox ratio	3.4,1.9,1.42,1,0.7,0.62	3.36,1.91,1.42,1,0.72,0.62	6.158,3.826,2.224,1.361,1,0.768	14.93,11.64,9.02,7.04,5.64,4.4,3.39,2.65,2.05,1.6,1.28,1

2.3 Simulation cycles

C-WTVC cycle in GB/T 27840-2011 and the CHTC cycle in GB/T 27840-2021 were input VECTO as simulation cycles for these four prototype vehicles, respectively.

The C-WTVC cycle adopts a unified test curve and consists of three parts: urban, rural and motorway, which is a total of 1800 seconds including urban driving time of 900 seconds, rural driving time of 468 seconds, and motorway driving time of 432 seconds. For different types of heavy commercial vehicles, the characteristic mileage distribution ratios in the three cycle intervals are determined, as shown in Table 3. The comprehensive fuel consumption of heavy-duty commercial vehicles is calculated by weighting the test results in each cycle interval.

Table 3 Classification of heavy-duty commercial vehicles and their characteristic mileage distribution proportions in GB/T 27840-2011

Vehicle type	**Max design total mass GCW/GVW/kg**	D_{urban}	D_{rural}	$D_{motorway}$
Trailer tractor	9000＜GCW≤27000	0	40%	60%
	GCW＞27000	0	10%	90%
Truck	3500＜GVW≤5500	40%	40%	20%
	5500＜GVW≤12500	10%	60%	30%
	12500＜GVW≤25000	10%	40%	50%
	GVW＞25000	10%	30%	60%
City bus	GVW＞3500	100%	0	0
Coach	3500＜GVW≤5500	50%	25%	25%
	5500＜GVW≤12500	20%	30%	50%
	GVW＞12500	10%	20%	70%

CHTC cycle consists of six test curves, which are the China heavy-duty commercial vehicle test cycle for city bus (CHTC-B), the China heavy-duty commercial vehicle test cycle for coach (CHTC-C), the China heavy-duty commercial vehicle test cycle for light-duty truck (GVW≤5500kg) (CHTC-LT), the China heavy-duty commercial vehicle test cycle for heavy-duty truck (GVW ＞ 5500kg) (CHTC-HT), the China heavy-duty commercial vehicle test cycle for dumper (CHTC-D) and the China heavy-duty commercial vehicle test cycle for trailer tractor (CHTC-TT). The comprehensive fuel consumption of heavy-duty commercial vehicles under CHTC is directly calculated from the measurement results under the corresponding test curve without any weighting.

3. Results and Discussions

The fuel consumption of four types of prototype vehicles under the C-WTVC and CHTC cycles were simulated and calculated using VECTO. The fuel used was B7 diesel and the CO2 emission conversion factor was 3.13. The load for these four vehicles was set to the total mass. The CO2 emissions of C-WTVC are weighted according to the characteristic mileage coefficient in Table 3.

3.1 Total CO2 emission results

The CO2 emission results of the four types of vehicles under the C-WTVC and CHTC cycles are shown in Figure 1. The coach has a largest CO2 emission of 902.65 g/km under CHTC, and the heavy-duty truck has a smallest CO2 emission of 477.58 g/km under C-WTVC. Compared with C-WTVC, the CO2 emissions of city bus, coach, heavy truck and trailer tractor all increased under CHTC, and the increase percentage were 19.09%, 19.03%, 1.51% and 5.23%, respectively. City bus and coach have the highest increase, trailer tractor have a lower increase, and heavy duty truck have the lowest increase.

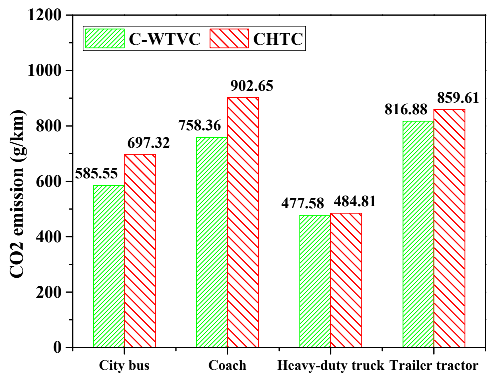

Figure 1 CO2 emission comparison under C-WTVC and CHTC cycles

Basically, CO2 emissions exhibit a positively correlated with the total vehicle mass., as shown in Figure 2. However, an exception is the trailer tractor and the coach. The trailer tractor mass is higher than coach, but the CO2 emission under CHTC of trailer tractor is lower than that of coach, indicating the cycle also has great effect on the CO2 emission.

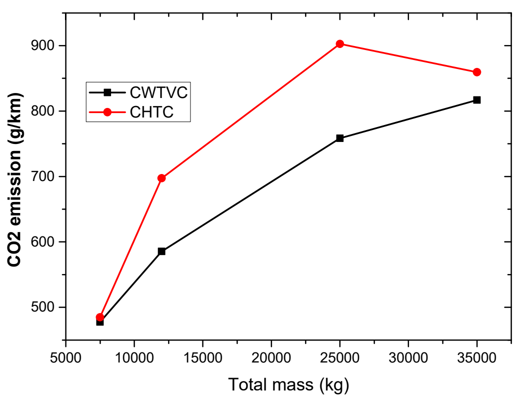

Figure 2 CO2 emission versus vehicle total mass

3.2 City bus

Table 4 shows the comparison of cyclic characteristic parameters between CHTC-B and the first 900 seconds (urban part) of C-WTVC. Compared to the C-WTVC cycle, the CHTC-B cycle runs longer, has higher maximum and average acceleration, lower average speed and maximum speed, and higher idle ratio.

Table 4 Characteristic parameters of CHTC-B and C-WTVC

Characteristic parameter	CHTC-B	Urban part of C-WTVC	Difference ratio(%)
Running time/s	1310	900	45.6
Distance/km	5.49	5.73	-4.2
Max speed/(km/h)	45.60	66.20	-31.1
Max acceleration/(m·s^{-2})	1.26	0.88	43.2
Max deceleration/(m·s^{-2})	-1.32	-1.00	32.0
Average speed/(km/h)	15.08	22.90	-34.1
Average running speed/(km/h)	19.43	27.21	-28.6
Average acceleration/(m·s^{-2})	0.48	0.39	23.1
Average deceleration/(m·s^{-2})	-0.54	-0.55	-1.8
Relative positive acceleration/(m·s^{-2})	0.17	0.15	13.3
Acceleration ratio/%	29.16	35.18	-17.1
Deceleration ratio/%	25.88	25.86	0.1
Cruise ratio/%	22.60	23.09	-2.1
Idle ratio/%	22.37	15.87	41.0

It can be seen from Figure 3 that the CO2 emissions of city bus increase with the increase of positive acceleration. Using the CO2 emission data points at acceleration above 0 to make a simple linear fitting, as shown in the small image in the upper left corner of Figure 3, and the slope is 10.7. The maximum acceleration and average acceleration of CHTC-B were 43.2% and 23.1% higher than those of C-WTVC, respectively, so the CO2 emission of CHTC-B is higher than C-WTVC.

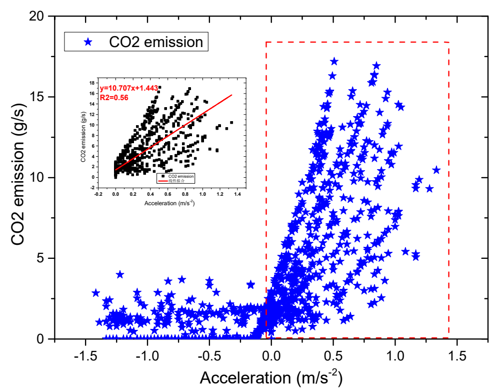

Figure 3 CO2 emission versus vehicle acceleration for city bus

3.3 Coach and heavy-duty truck

Characteristic parameters of CHTC-C, CHTC-HT and C-WTVC is shown in Table 5. Compared with the C-WTVC cycle, the idle ratio and maximum acceleration were higher for the CHTC-C and CHTC-HT cycles. The average acceleration and average travel speed of CHTC-C are the highest, followed by C-WTVC, and the lowest in CHTC-HT.

Table 5 Characteristic parameters of CHTC-C, CHTC-HT and C-WTVC

Characteristic parameter	CHTC-C	CHTC-HT	C-WTVC	Difference ratio between CHTC-C and C-WTVC (%)	Difference ratio between CHTC-HT and C-WTVC (%)
Running time/s	1800	1800	1800	0	0
Distance/km	19.62	17.33	20.51	-4.3	-15.5
Max speed/(km/h)	95.7	88.5	87.8	9.0	0.8
Max acceleration/(m·s^{-2})	1.25	1.14	0.88	42.0	29.5
Max deceleration/(m·s^{-2})	-0.13	-1.21	-1.00	-87.0	21.0
Average speed/(km/h)	39.24	34.65	41.00	-4.3	-15.5
Average running speed/(km/h)	47.98	40.16	45.52	5.4	-11.8
Average acceleration/(m·s^{-2})	0.43	0.31	0.36	19.4	-13.9
Average deceleration/(m·s^{-2})	-0.48	-0.45	-0.48	0.0	-6.2
Relative positive acceleration/(m·s^{-2})	0.10	0.09	0.09	11.1	0.0
Acceleration ratio/%	26.22	24.22	28.76	-8.8	-15.8
Deceleration ratio/%	22.56	18.06	22.87	-1.4	-21.0
Cruise ratio/%	33.00	44.00	38.53	-14.4	14.2
Idle ratio/%	18.22	13.72	9.94	83.3	38.0

In Figure 4, the CO_2 emissions of coach and heavy-duty truck also show an increase with the increase of positive acceleration,with a slope of 24.02 for coach and 7.78 for heavy-duty truck, respectively. The CO_2 emission of coach is more relevant to positive acceleration. While the maximum acceleration and average acceleration of CHTC-C are 42% and 19.4% higher than those of C-WTVC, respectively, that's why the CO_2 emission of CHTC-C is higher than C-WTVC. For CHTC-HT, the average acceleration is 13.9% lower than C-WTVC although the maximum acceleration is 29.5% higher than C-WTVC. The trade-off between the maximum acceleration and the average acceleration, leading to a minor CO_2 emission increase for heavy-duty truck.

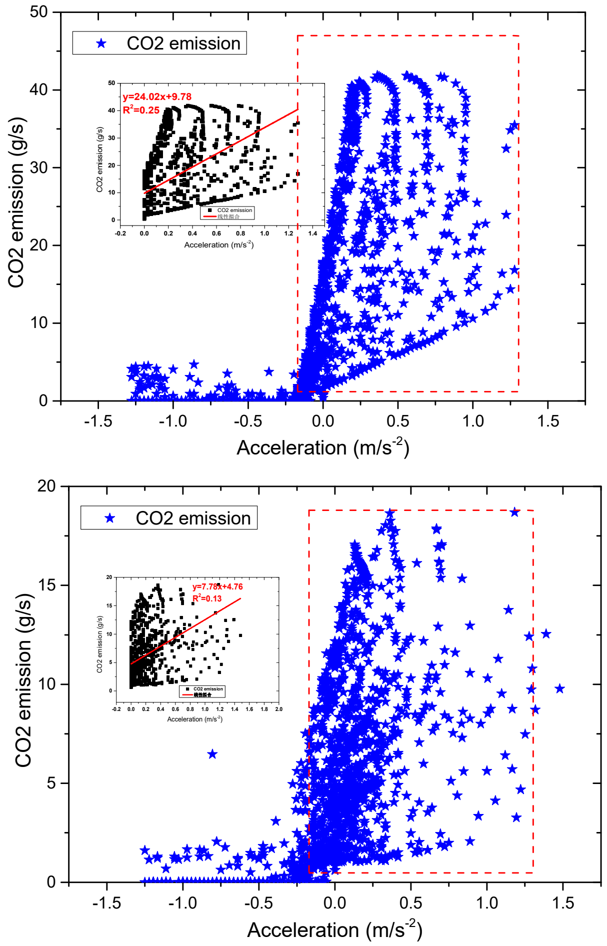

Figure 4 CO_2 emission versus vehicle acceleration, left: coach, right:heavy-duty truck

3.4 Trailer tractor

Table 6 lists the characteristic parameters of CHTC-TT and the last 900 seconds of C-WTVC (rural and motorway part). Compared to the C-WTVC cycle, the maximum acceleration is increased by 8%, the average acceleration is decreased by 9.7%, and the average speed is decreased by 21.4%. Moreover, CHTC-TT also includes some urban conditions, while C-WTVC only include rural and motorway parts.

Table 6 Characteristic parameters of CHTC-TT and C-WTVC

Characteristic parameter	CHTC-B	Rural and motorway part of C-WTVC	Difference ratio(%)
Running time/s	1800	900	100.0
Distance/km	23.22	14.78	57.1
Max speed/(km/h)	88.00	87.80	0.2
Max acceleration/(m·s-2)	0.81	0.75	8.0
Max deceleration/(m·s-2)	-1.04	-1.00	4.0
Average speed/(km/h)	46.44	59.05	-21.4
Average running speed/(km/h)	50.82	61.51	-17.4
Average acceleration/(m·s-2)	0.28	0.31	-9.7
Average deceleration/(m·s-2)	-0.36	-0.40	-10.0
Relative positive acceleration/(m·s-2)	0.06	0.07	-14.3
Acceleration ratio/%	17.44	22.31	-21.8
Deceleration ratio/%	15.78	19.76	-20.1
Cruise ratio/%	58.17	53.94	7.8
Idle ratio/%	8.61	4.00	115.3

The CO2 emissions of trailer tractor show an dramatic increase with the increase of positive acceleration,with a slope of 33.59. It seems that the slope is positively related to the vehicle mass, meaning that the positive acceleration has a more stronger effect on CO2 emission for a heavier vehicle.

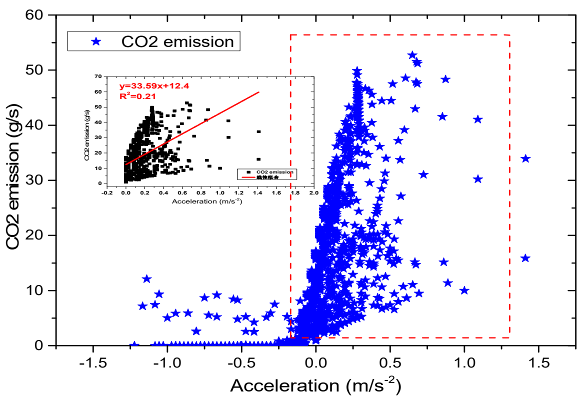

Figure 5 CO2 emission versus vehicle acceleration for trailer tractor

3.5 Effect of test cycle on engine conditions

Table 7 shows the time ratio of each gear during the C-WTVC and CHTC for four different vehicles. The test cycle has a great effect on the gear selection during driving, then to affect the engine run conditions. For city bus, CHTC-B direct gear (6 gear) only takes 16% of the time, while C-WTVC reaches 60%, due to the lower average speed and higher idle ratio. For trailer tractor, the highest gear (12 gear) takes 41% of the time for CHTC-C, but 51% for C-WTVC due to a higher average speed.

Table 7 Time ratio of each gear during the C-WTVC and CHTC

Vehicle	Time ratio(%)	N	1	2	3	4	5	6	7	8	9	10	11	12
City bus	CHTC-B	24	21	7	10	16	5	16	-	-	-	-	-	-
	C-WTVC	11	9	3	6	8	4	60	-	-	-	-	-	-
Coach	CHTC-C	28	11	9	6	14	4	28	-	-	-	-	-	-
	C-WTVC	22	10	9	8	18	12	21	-	-	-	-	-	-
Heavy-duty truck	CHTC-C	22	10	7	10	21	15	15	-	-	-	-	-	-
	C-WTVC	19	8	3	9	26	14	21	-	-	-	-	-	-
Trailer tractor	CHTC-C	16	1	1	1	5	1	4	2	5	6	6	11	41
	C-WTVC	12	0	0	1	2	1	1	1	1	7	13	11	51

4. Conclusion

CO2 emission of four types of vehicles including city bus, coach, heavy-duty truck and trailer tractor were calculated by VECTO with the simulation cycles of C-WTVC and

CHTC. The results show that CO_2 emissions of CHTC are higher than that of C-WTVC for these four types of vehicles with increase percentages ranging from 1.5% to 19%. City bus and coach have the highest increase percentage, followed by trailer tractors, and heavy-duty truck have the lowest increase percentage. For different cycles, average acceleration difference is the most predominant factor for the CO_2 emission, followed by driving strategy changes. For different types of vehicle under the same cycle, the mass or load has a direct relationship to CO_2 emission. Heavy-duty vehicle CO_2 emissions rise as the vehicle accelerates, and the upward trend becomes more pronounced as the total mass increases.

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