ANALYSIS OF ENERGIES AND SPEED PROFILES OF DRIVING CYCLES FOR FUEL CONSUMPTION MEASUREMENTS

Denis Makarchuk[1], Juris Kreicbergs[1], Aivis Grislis[1], Maris Gailis[1, 2]
[1]Riga Technical University; [2]Latvia University of Agriculture
denis.mkk@gmail.com, juris.kreicbergs@rtu.lv, aivis.grislis@rtu.lv, maris.gailis@rtu.lv

Abstract. Fuel consumption of a vehicle ($l \cdot 100\ km^{-1}$) is determined in a test procedure, during which the vehicle is being driven along a defined speed profile. Apart from the procedure specifications, the speed profile itself has a major impact on the resulting fuel consumption. In this paper four important driving cycles are compared – NEDC, WLTC, FTP75 and HWY. First, just cycle speed profiles are compared by mean, maximal and minimal values. Cycle speed distribution is used as an additional method of comparison. The next step is to assess engine operation in the cycle. For this purpose a representative vehicle was defined, using the data of US EPA database. With vehicle data power and energy in the cycle can be calculated. These data are then plotted in a 3D histogram, which in this case represents the engine map. This kind of diagram enables assessment of energy distribution in the engine map, although transmission influence is not taken into account. Lastly, in the cycle the consumed energy dependence on the vehicle class is determined. The analysis shows that WLTC offers the most homogeneous distribution of all in this paper analyzed cycles.

Keywords: driving cycle, NEDC, WLTC, FTP75, HWY, fuel consumption, speed distribution, energy distribution, engine map.

Introduction

In the last few decades automotive emission norms have been reduced very significantly. Aside from the reduction of the limits on toxic exhaust gas emissions and introduction of new emission norms (particulate number), CO2 emission and consequently the fuel consumption limits have also been reduced. It is becoming more and more complicated for manufacturers to stay within these limits. They struggle to find any additional potential for reducing the fuel consumption, and sometimes find it in the test procedure rather than in the vehicle itself.

It is a well-known fact that fuel consumption certification values in Europe are no longer realistic [1; 2; 3]. Discrepancies between the real-world fuel consumption and certified values are caused both by test procedure deficiencies and vehicle properties (drivetrain, transmission and engine efficiency). However, cycle speed profiles alone play an important role in standardized fuel consumption measurement, and it is important to understand deeper their influence on the measurement.

A lot of different driving cycles exist in the automotive industry. This is becoming an issue, since the same vehicle can be certified in different markets. It means that the vehicle has to be separately type-approved in each of these markets by carrying out the corresponding test procedure.

The development of Worldwide harmonized Light duty vehicles Test Procedure (WLTP) is thought to solve this problem. A corresponding cycle WLTC was developed, which is thought to be more realistic than the existing cycles [4]. However, it is not very obvious in which way the cycle quality can be defined, estimated and compared.

Some of the cycles come from legislative type-approval procedures; others are alternative non-legislative cycles used mostly in research. In this paper only legislative cycles for type approval fuel consumption and emission measurement were analyzed. Since it is impossible to make a detailed comparison of all existing cycles in one paper, only several commonly used cycles were defined.

Before starting any kind of comparison it is important to understand what the key properties and main tasks of the cycles are. One of the most important tasks is – allowing a realistic measurement of fuel consumption. It means that the speed profile should be based on real measured data. In this way loads on the vehicle and engine would be correlating to real life values.

Vehicle comparison should be meaningful. A better developed and calibrated vehicle should have lower certified fuel consumption. This leads to another requirement – a cycle should cover preferably a broader range of engine (and transmission) speeds and loads. In this way driving styles of different drivers would be represented.

Furthermore, the cycle should not be developed in a way that it is possible to significantly reduce total fuel consumption in the cycle by optimizing only a few distinguishable engine operating points.

The energy distribution in the engine map should play an important role in cycle comparison. It is not possible to completely avoid example vehicle use in the cycle comparison, since energy (or power) in the cycle is dependent on the vehicle mass and coast down parameters.

Materials and methods

Firstly, a representative vehicle should be defined. For definition of the vehicle mass and coast down performance of the representative vehicle an EPA database was used [5]. Corresponding data of all in US certified vehicle models and makes from 2009 to current year were picked from the EPA database for current analysis. This resulted in a data array consisting of more than 24000 records. These are, however, not unique vehicles. Some vehicles were tested in several cycles; some of them have for the data in question insignificant differences (e.g., gearbox). Apart from that, several other filter criteria had to be applied.

For definition of a representative vehicle not all coast down data could be used. The measured coast down data have a form of three coefficients A, B, and C. These are the coefficients of a quadratic approximation function for the resistance force F_{res} as a function of velocity:

$$F_{res}(v) = A + Bv + Cv^2 , \tag{1}$$

where v – vehicle speed, km·h^{-1}.

For further calculations it is more convenient to use physical quantities – air drag coefficient c_w and rolling resistance factor f. In this case total vehicle resistance force (without consideration of grade) is described as follows:

$$F_{res}(v) = mgf + 0.5 c_w A \rho v^2 , \tag{2}$$

where m – vehicle mass, kg;
g – gravitational acceleration, m·s^{-2};
A – vehicle frontal area, m^2;
ρ – air density, kg·m^{-3}.

As it can be directly seen, the physical approach of equation (2) does not have any factor, which is linearly dependent on vehicle speed. Reduction of B to c_w and f in this case is not possible, which means that only vehicles with B coefficient close to 0 may be used for further analysis. In this case calculation of f and $c_w{\cdot}A$ from the corresponding A and C coefficients is very simple. Thus only vehicles with $-0.00001<B<0.00001$ were selected for further evaluation. Furthermore, vehicles with $c_w{\cdot}A > 1$ were filtered out as irrelevant or unrealistic.

After recalculation and filtering the parameters 234 unique vehicles remained. The distribution of $c_w{\cdot}A$ and vehicle mass of the remained vehicles is plotted in Fig. 1.

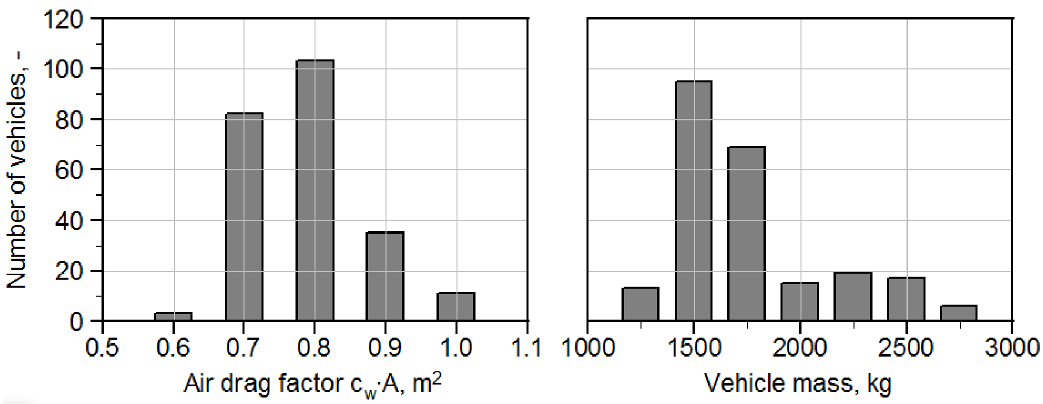

Fig. 1. **Distribution of vehicle $c_w{\cdot}A$ (left) and mass (right) in the data set**

It should be taken into account, that the database of in US certified vehicles was used. In the US the distributions of vehicle classes tend to be shifted to higher class vehicles (hence higher mass and frontal area). The effect of vehicle class on the rolling resistance factor is assumed to be negligibly small, so an average value was used. Distribution values of vehicle parameters are summarized in Table 1.

Table 1

Distribution of vehicle parameters in database

Total vehicles	234		
	Vehicle mass, kg	Roll. resistance factor	Air drag factor $c_w{\cdot}A$, m^2
Average	1750	0.010	0.785
Standard deviation	335	0.002	0.080

Four cycles – NEDC, WLTC, FTP75 and HWY – were defined for analysis. First, purely cycle speed profiles were analyzed. The main advantage of such analysis is that it is independent of the vehicle. The basic cycle data are summarized in Table 2.

Table 2

Cycle data

Parameter	**NEDC**	**WLTC**	**FTP75**	**HWY**
Duration	19 min 40 s	30 min	31 min 15 s	12 min 45 s
Distance, km	10.90	23.30	17.80	16.50
Stop duration, %	23.70	12.60	17.90	0.10
Max. speed, km·h^{-1}	120.00	131.30	91.20	96.40
Average speed, km·h^{-1}	33.40	46.50	34.10	77.70
Average speed w/o stops, km·h^{-1}	43.80	53.20	41.60	78.20
Max. acceleration , m·s^{-2}	1.06	1.67	1.47	1.43
Min. acceleration , m·s^{-2}	-1.39	-1.50	-1.47	-1.48

FTP75 cycle for the study was used without 10 min intermediate stop prescribed by the test procedure. NEDC in this case is the cycle for vehicles with automatic transmissions. Data of all cycles were interpolated to have equal 0.1 s time step. Overview of the cycle profiles can be seen in Fig. 2.

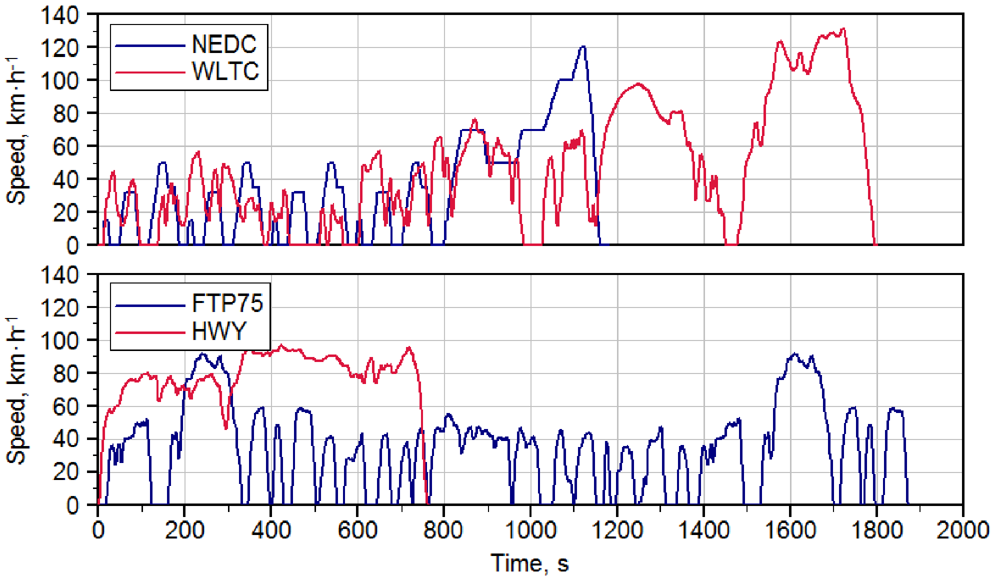

Fig. 2. **Cycle speed profiles**

The WLTC was developed based on the measured data, which included the average trip time and distance [4]. On contrary to WLTC, NEDC is a synthetic cycle. Duration and distance of WLTC and NEDC differ significantly. Apart from direct influence on such cycle values as the testing time and engine work, duration and distance affect also other cycle characteristics, for example, the importance of cold starting phase. The relatively short duration of NEDC puts more priority on cold engine operation, which, in turn, means that the optimization of engine operation in this phase has a significant impact on the total fuel consumption in the cycle.

Another similar example is the stop duration – longer stop duration in NEDC played an important role in introduction of a start-stop feature in modern cars. There is still discussion ongoing if this technology really brings a benefit in real life driving, especially taking into account additional costs and maintenance. The real benefit in fuel consumption is less than measured in NEDC [6].

The maximal speed of NEDC and, especially WLTC, may seem unrealistically high for some European countries. In contrast, US cycles have maximum speed values, which are closer to real highway speed limits. However, higher maximum speed of WLTC drives the engine in higher speed and load range of the map, which means that manufacturers will have to optimize the engine also for these operating conditions.

Maximal acceleration of NEDC is very low compared to transient cycles. The values of FTP75 and HWY are significantly higher, although they still were limited by test bench capabilities of that time (tire slip on the rollers). WLTC has the highest maximal acceleration of all cycles, which is thought to be more realistic. However, these are only peak values, which represent only one point in the whole cycle.

The influence of the vehicle class on total traction energy in cycles also should be analyzed. Energy calculation was done in a spreadsheet, where depending on the vehicle speed firstly the resistance force has been calculated, then a corresponding power, and lastly power was integrated over time. For traction energy, only positive total force has been integrated. The calculation process can be summarized in equation (3).

$$E_{trac} = \sum_{t=0}^{T} \max\left(F_{rolres} + F_{drag} + F_{inert};0\right)v\Delta t\,, \tag{3}$$

where E_{trac} – energy for traction, J
F_{rolres} – rolling resistance force, N
F_{drag} – air drag force, N
F_{inert} – inertia force, N
v – vehicle speed, m·s^{-1}
t – time, s
T – total cycle duration , s

To evaluate engine operation a reference vehicle should be defined which includes its coast down performance and transmission. However, it is desirable to leave transmission out of evaluation. First of all, it is done for simplicity purpose; secondly, it is desirable to bring as little specific vehicle data in cycle evaluation as possible, because the purpose of the paper is solely cycle evaluation.

Only vehicle coast down data are necessary for energy calculations. For evaluating the influence of the vehicle class, 5 different vehicle classes were defined based on previously processed data. They are shown in Table 3.

Table 3

Definition of the vehicle classes

Vehicle class	Low	Basic	Basic-High	High	Extra-High
Formula	Avrg – 2σ	Avrg – σ	Average	Avrg + σ	Avrg + 2σ
Vehicle mass, kg	1080	1415	1750	2085	2420
Air drag factor $c_w \cdot A$, m^2	0.625	0.705	0.785	0.865	0.945
Rolling resistance factor, -	0.01				

Vehicles in the US market tend to be bigger than in Europe, so average values of the US database were signed to the basic-high vehicle class.

Results and discussion

One of the important goals of the cycle is to load the engine preferably in the broader range of the engine map and to load it as homogeneous as possible. One way to assess it is by the help of speed histogram, shown in Fig. 3.

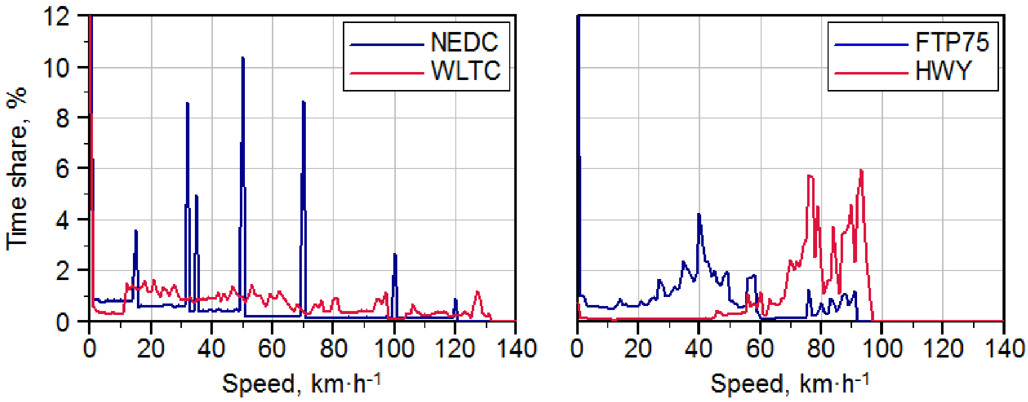

Fig. 3. **Cycle profile histograms**

From Figure 3 the synthetic origin of NEDC is directly seen: the histogram shows peaks at constant speed values (15, 32, 35, 50, 70, 100 and 120 km·h^{-1}). Between these peaks the histogram is flat due to constant acceleration values. Contrary to NEDC, WLTC has more or less homogenous speed distribution with slightly higher values in the range under 70 km·h^{-1} (city driving). FTP75 puts more importance on city driving with expressed maximum around 40 km·h^{-1}, almost no cover of speeds between 60 and 75 km·h^{-1} and little cover of highway driving. These drawbacks are tolerated by the HWY cycle (for certification both of these cycles have to be used), which is driven at high speeds. Speed histograms give a lot more information on speed profile of the cycle, although they still are lacking any evaluation of engine operation in the cycle.

Detailed energy consumption of basic class vehicle has been analyzed. For this purpose a 3D histogram was chosen, where time share was plotted vs. vehicle speed and power (Fig. 4).

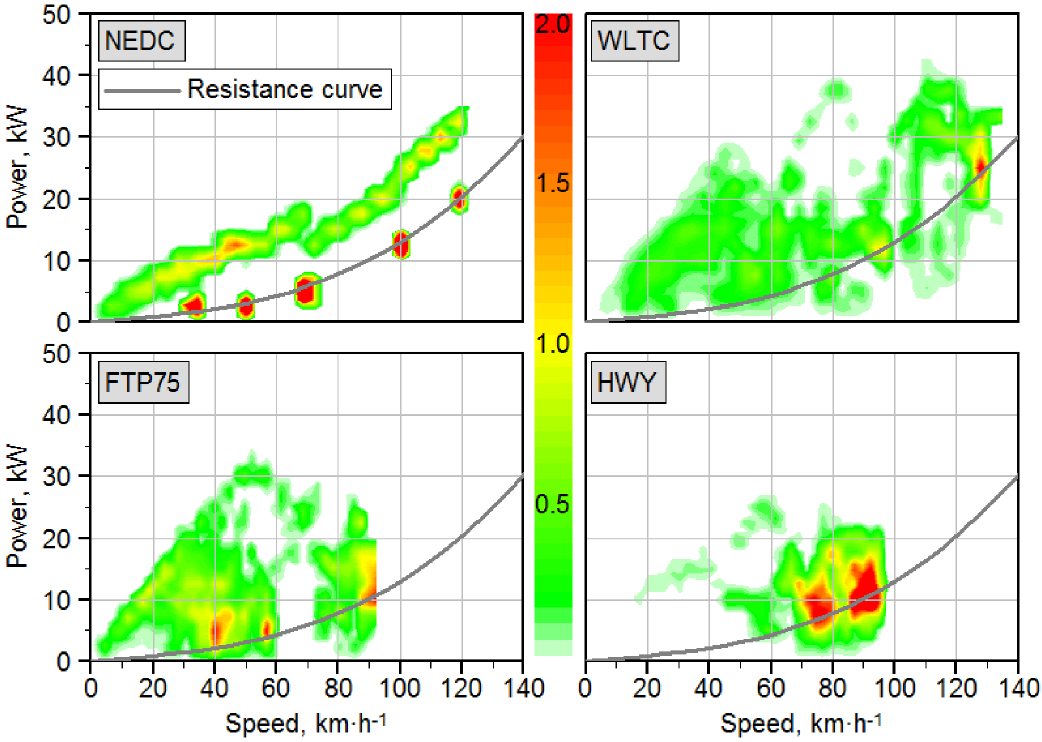

Fig. 4. **Energy share diagram**

From this diagram it can be seen, that energy distribution in NEDC is very discrete. Significant amounts of energy are consumed in constant driving phases, however, also transient phases are noticeable, since most of accelerations are equal. Energy distribution in FTP75 is a lot better than in NEDC, although a few points are still standing out. Also the blank spot between 60 and 70 km·h^{-1} is clearly visible. HWY cycle has two relatively big regions, where most of the energy is consumed. WLTC has the biggest covering of the map of all analyzed cycles. The city part (up to 70 km·h^{-1}) is very homogenous, which means that the corresponding region of the engine map will have to be optimized in order to get fuel consumption benefit. In the highway part, one can find a distinct operating point at 130 km·h^{-1}, where more energy is consumed. The reason for that is the speed itself – due to air drag the power demand at this speed is a lot higher, thus even little time in this operating point takes a significant amount of energy. Also the total area of the city part of the map is significantly bigger than the area of the highway part, meaning that city fuel consumption will be dominant in the total vehicle fuel consumption rating.

Lastly, the influence of the vehicle class on the total engine energy in the cycle was evaluated (Fig. 5).

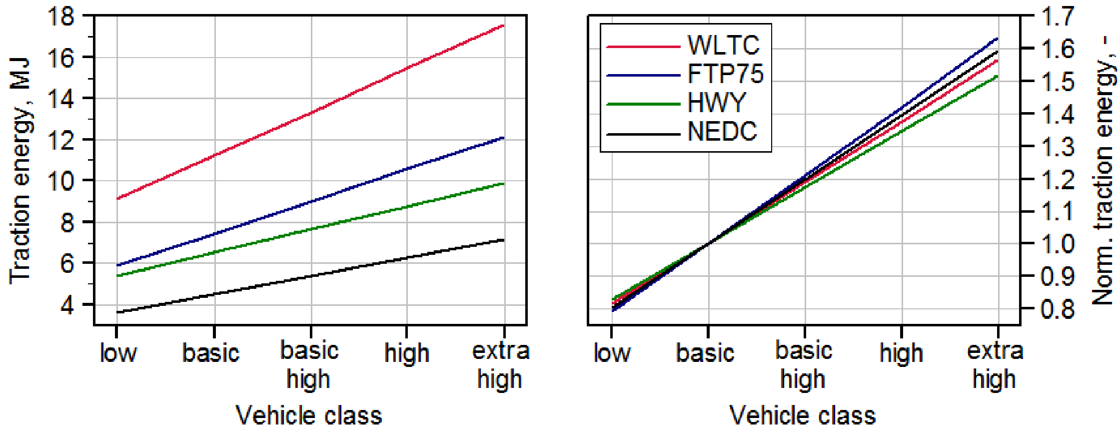

Fig. 5. **Vehicle mass variation in all cycles**

In the left diagram of Fig. 5 absolute energy values are shown. As it can be seen, WLTC has by far the highest traction energy demand, although FTP75 is even slightly longer. This speaks for itself – the power demand in WLTC is a lot higher than in other cycles. NEDC, on the other hand, has the lowest energy demand of all.

Total traction energy dependence on the vehicle class can be better seen in the right diagram (Fig. 5), where energy values were normalized to the basic vehicle class, hence the value 1 in all cases. Interestingly, despite WLTC has the highest accelerations in comparison to other cycles, the dependency of traction energy on the vehicle class (which implies vehicle mass and air drag) is even slightly lower than of NEDC. The reason for that does not lie in accelerations in the cycle. Accelerations have no direct influence on the traction energy. The traction energy is in fact energy lost in the cycle: it is a sum of energy loss due to rolling resistance, air drag and braking. Sum of the first two depend on the vehicle speed, the last one depends on the amount of the braking phases. FTP75 has a lot more braking phases in comparison to other cycles, which is directly reflected in this diagram. In WLTC, on the other hand, although it is transient, not so much kinetic energy is lost due to braking, which is the reason why it lies slightly lower than NEDC.

Conclusions

1. The cycle speed profiles have an influence not only on the fuel consumption, but also on the technologies applied to the vehicle for fuel consumption reduction. It sets special demands on the cycle for legislative purposes – it should be close to real driving, so that the technologies brought into the vehicle bring a real fuel consumption improvement.
2. The cycle comparison methods have shown that synthetic NEDC speed profile results in a very discrete energy distribution in the engine map, which is a drawback, since it makes selective optimization possible.
3. The transient cycles, which seem to offer a very homogenous speed distribution, not necessarily offer a homogeneous energy distribution, as in case with FTP75.
4. From the energy point of view, WLTC offers the most homogeneous distribution of all in this paper analyzed cycles. The main advantage of it is that one cannot improve fuel consumption in WLTC by selectively optimizing the engine map. Furthermore, with a transient cycle, it is at least complicated to use the cycle detection technique for reducing fuel consumption.

References

1. Ntziachristos L., Mellios G., Tsokolis D., Keller M. and Hausberger S. In-use vs. type-approval fuel consumption of current passenger cars in Europe. Energy Policy, Volume 67, April 2014, pp. 403-411.
2. Mock P., German J., Bandivadekar A. and Riemersma I. Discrepancies between type-approval and "real-world" fuel-consumption and CO2 values. The International Council on Clean Transportation, 2012. 13 p.
3. Mock P., Kühlwein J., Tietge U., Franco V., Bandivadekar A. and German J. The WLTP: How a new test procedure for cars will affect fuel consumption values in the EU. International Council on Clean Transportation, 2014. 20 p.
4. Tutuianu M., Marotta A., Heinz S., Ericsson E., Haniu T., Ichikawa N. and Ishii H. Development of a World-wide Worldwide harmonized Light duty driving Test Cycle (WLTC). UNECE, Technical report, 2013. 97 p.
5. Test Car List Data Files "US Environmental Protection Agency" [Online] [06.02.2015]. Available at: http://www.epa.gov/OMS/tcldata.htm
6. Wishart J., Shirk M., Gray T., Fengler N. "Quantifying the Effects of Idle-Stop Systems on Fuel Economy in Light-Duty Passenger Vehicles," SAE Technical Paper 2012-01-0719, 2012, doi:10.4271/2012-01-0719. 24 p.