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Statistical evaluation of driving cycle with slope variability

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Recently, the scientific community has assessed evidence that exposure to outdoor air pollution causes lung cancer and increases the risk of bladder cancer. Because air pollution in urban areas is mainly caused by transportation, it is necessary to evaluate pollutant exhaust emissions from vehicles during their real world use. Nevertheless, their evaluation and reduction is a key problem, especially in the cities, that account for more than 50 percent of world population. A correct evaluation of pollutant emissions and fuel consumption by vehicles in real use and precisely geolocated in a road is an important activity and it is still open in the international scientific contexts. Several experimental campaigns were carried out with some cars instrumented for both the acquisition of kinematic data, polluting emissions in continuous, and GPS latitude, longitude and altitude data for the correct geolocalization and slope variation during a path. In the context of qualitative and quantitative study of correlation between kinematic sequences/emission/geographical position, the aim of this paper is a statistical evaluation of the slope variability along streets during each journey performed by the instrumented vehicle. Therefore, through a multivariate statistical approach, this type of gradient analysis permits the correlation study of the emission profiles and consumption for a specific road position and the evaluation of the influence on their behavior.

keywords: Driving cycle, emissions, fuel consumption, slope, urban environment.

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1 Introduction

The air quality of urban environments has become more important in recent years. Control of air quality affected by traffic emission is vital for human health. Vehicular emissions are one of the major sources of air pollutants in the urban environment. Although several studies of pollutant emission are made (André et al., 2006; May et al., 2013) just few of them (Wood et al., 2014; Prati et al., 2014; Wyatt et al., 2014; Sentoff et al., 2015; Carrese et al., 2013) took into account the change in altitude in city traffic evaluation and the possible influence on emissions variation. The evaluation of the emission produced by vehicles in correspondence of determined traffic situation in a defined road with specified traffic management rules is generally carried out by multiplying emission factors per vehicle activity, obviously considering different vehicle types. The problem is thus, in principle, defined when the following information is available:

- Road characteristics (number of lanes, type of pavements, crossing).
- Traffic management rules (traffic lights, parking, speed limits, ...).
- Vehicle composition (fleet composition, vehicle age distribution, ...) and activity.
- Vehicle flow and density, congestion level of road.

In recent years we are seeing positive results, but on a national scale we are still far from achieving this goal. To obtain the emission factors, consolidated methods make reference to vehicle mean velocity, which can be easily obtained by vehicle flow and density in the road. In this framework a statistical approach has been proposed capable to consider more attributes than the simple speed to characterize driving behavior, not only in the determination of driving cycles (DCs) but also in the emission modeling (Rapone et al., 1995, 2005). Many research programs have been carried out on this subject, whose aim was to determine driving behavior and emission trends. Preliminary results show that, if we consider a specific road, driving behavior changes and so driving cycles of different characteristics always occur (Ferulano et al., 2000; Hickman and and McCrae, 2003; André M., 2004). In this context, it could be interesting also to suggest paths based not only on the minimum distance, but on the minimization of fuel consumption as a function of the geomorphological features of the territory. An experimental campaign in the hilly area of Naples city is realized by PEMS (Portable Emission Measurement Systems) equipment (Weiss et al., 2011; Franco et al., 2014; Watson et al., 2012). Some results relative to tests performed on road, with a new Fiat 500 TwinAir turbo with 875cc displacement homologated EURO 5 (gasoline powered), are presented.

2 Experimental Activity

The Fiat 500 TwinAir has been instrumented for on-road tests as shown in the following Figure 1. The main components of the monitoring system used in this work are:

- a Semtech gas analyzer produced by Sensor to measure at 1Hz CO, NOx and CO_2 emissions. This analyzer uses NDIR cell (Non-Dispersive Infrared) for CO and CO_2 measurements, NDUV cell for NO/NO_2 and separate electrochemical sensor for oxygen. The analyzer is calibrated on a regular basis and zeroes itself on start-up using outside air;
- an EFM (Exhaust Flow Meter) by Sensor;
- an OBD interface and logging computer running proprietary software (EDS) to acquire engine operating parameters (speed, rpm, engine air flow);
- a GPS receiver by Racelogic Ltd to acquire the spatial position;
- a video camera to record traffic situations.

The signals from all devices have been synchronized by using the same information obtained from different sources (i.e. speed from GPS and OBD).

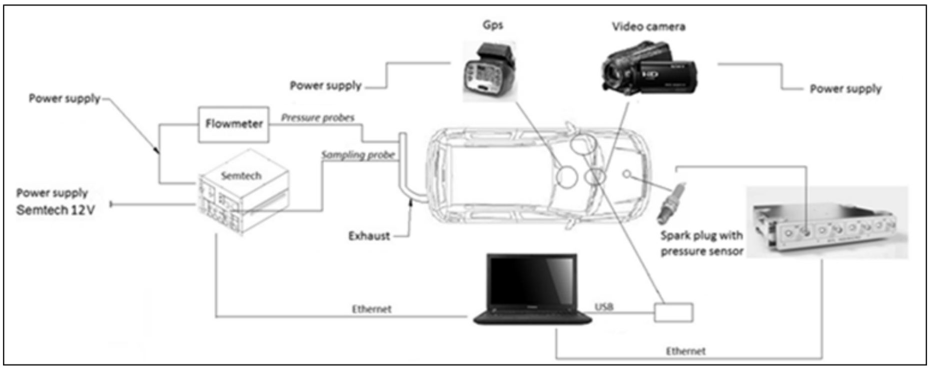

Figure 1: Experimental route: the hilly area of Naples (VMR Path)

During the experimental campaign, instrumented car performed some missions in the city of Naples along a traffic busy route. In particular, in this paper, we referred especially to the hilly area of Naples city, named VRM Path (figure 2), characterized by roads with numerous elevation changes (figure 3) and a path length of about 8 km. Path has an average uphill of 6.9%, while downhill has an average gradient of 6.5%. Overall, one road tests have been performed to make a comparison between the acquisition data in real use and the dynamometric test bench in the lab.

A repetition of VMR Path driving cycle acquired on-road (WMR Road) was three times realized[1] in laboratory (WMR_LAB_R1-3) and exhaust emissions were measured and analyzed. In this context this paper tries to give a contribution to the evaluation and comparison of the fuel consumption and emissions during road tests performed

[1]Usually, the recorded road speed profile is repeated at least three times on the dynamometer test bench with the related acquisition of the emissions profile. The repetitions are used for the emission values's validation.

Figure 2: Experimental route: the hilly area of Naples (VMR Path) with slope variability

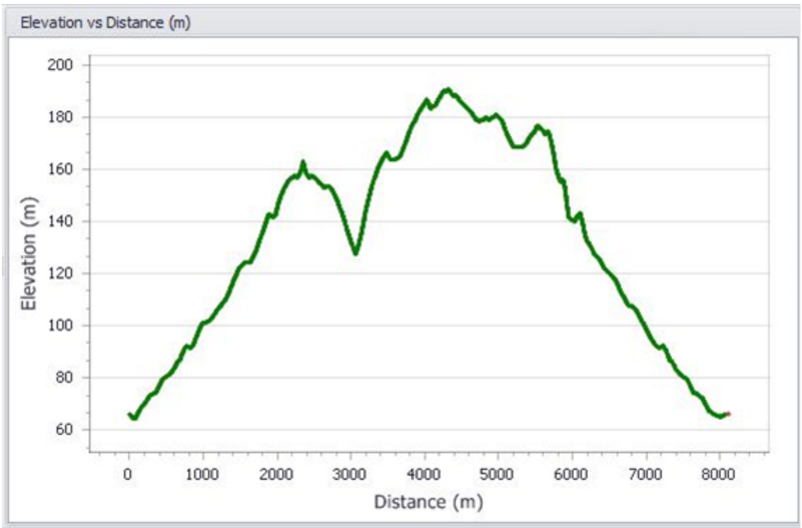

Figure 3: Experimental route: elevation profile of the hilly area of Naples

in real use by PEMS (Portable Emission Measurement System) and repeated on the chassis-dynamometer.

3 Statistical Evaluation

The velocity profile of each recorded trip is segmented in a succession of sequences, so that a sequence is the part of motion of a vehicle between two successive stops. Driving cycles have been determined without any conditioning of data respect to road network, but keeping the information detected on road, in terms of GPS coordinates latitude, longitude and altitude, when applicable. The method utilized to determine the driving cycles is based on sequence characterization. To characterize the sequence pattern the identified variables are partially related to the dynamic vehicle equation, plus idling time to consider standstill phase emission production and partially to slope variability. These variables are identified by considering emission variation as explained by the variation in exhaust mass (function of energy spent by the vehicle in a driving cycle), and the frequency of acceleration events at different speeds (1). Moreover, the variables were identified considering two potential causes of variability in emissions for a driving cycle: energy expenditure from the vehicle in the cycle and the acceleration events at different speeds (Joumard et al., 2007; Rapone et al., 2008).

$$M \approx \int P(t)\,dt \approx \int_t (a_0 + a_1 * v(t) + a_2 * v^2(t) + M_{va} * (a(t)) * v(t)dt \qquad (1)$$

where M is the total mass of exhaust, *P(t)* the engine power, *v(t)* the speed, *a(t)* the acceleration and M_{va} the vehicle effective mass. In Table 1, variables characterizing driving behavior are reported.

Table 1: Variables characterizing driving behavior

Variable	Description
mv (km/h)	Mean of running speed (v>0)
$mv^2 (km^2/h^2)$	Mean of square speed (v>0)
$mv^3 (km^3/h^3)$	Mean of cube speed (v>0)
Tral (s)	idling time v=0 in second
Trunning (s)	total running time (v>0) in second
Dist (m)	distance covered
Tseq (s)	Total duration of the sequence (s)
m_vapos (m^2/s^3)	Mean of instantaneous values of product (a(t)v(t)) when v(t)>0 and a(t)>0
DS1 (%)	%time with delta slope <-0.70 meters (m)
DS2 (%)	%time -0.70<= delta slope <-0.20 meters (m)
DS3 (%)	%time -0.20<= delta slope <0 meters (m)
DS4 (%)	%time 0<= delta slope <0.20 meters (m)
DS5 (%)	%time 0.20<= delta slope <0.70 meters (m)
DS6 (%)	%time with delta slope >=0.70 meters (m)

We carry out the PCA analysis for dimensionality reduction (retain variance and build orthogonal variables) and then subsequently the CDA, that reproduce analysis in the each cluster but using as variables PCA components. By CDA, we attempts to classify driving cycle, with cluster membership, and obtain the two dimensions that provide maximum separation among the clusters. Elevation values are processed obtaining six variables, DS1-DS3 describing downhill road and DS4-DS6 uphill road. They represent the percentage variation relative to the sequence duration. Values that define the ranges of the variables DS1-DS6 in the Table 1 are derived from the study of the distribution of frequencies of the incremental delta slope (Meccariello and Della Ragione, 2014). Here was mainly analyzed problems relating to errors on the measurement of the slope and its influence on emissions and consumption. Moreover, the analysis was conducted by identifying kinematic sequences, while in this paper a deep analysis was performed on a DCs, that are a succession of similar sequences. The values calculated for a sequence constitutes a multivariate observation X. Therefore, observations (sequences) must be analyzed utilizing multivariate statistical methods. Since a considerable number of variables represents a sequence and these are mutually correlated, a Principal Component Analysis (PCA) is performed. Principal components (PC) are latent variables function of variables of Table 1, calculated by the matrix of observed $X(i, j)$, where $i=1,k$ and $j=1,NS$; k are the 14 identified variables, NS are the total number of sequences which in this case study are 128. Each PC tends to characterize different typical features of sequences by a group of correlated variables, separating for example sequences with high mean speed and long running time and low acceleration, from sequences with low mean speed, high idling time and acceleration. Referring to the analysis, the first eight components explain about the 97% of driving cycle variability, while the first four components explain almost 76.39%. In this analysis, most variability was explained by the first two components with about 60%[2]. In Table 2 a factor pattern table, to understand which items load highly on which factors and then determine what items have in common, is reported. The first component characterizes the sequences with higher mean speed (*mv*)[3] and longer duration (*tseq*). The second component, instead, characterizes the sequences with negative slope (DS1, DS2), respect to the sequences with positive slope (DS5, DS6). This approach allows us to understand the effect and the differences of all DCs through the identified variables.

Clustering of sequences by multivariate statistical analysis give the basic information to cut automatically driving cycles from the real velocity profile detected on the road. A new cycle starts when a sequence belonging to a different cluster is encountered in the car speed time series slope (Della Ragione et al., 2013). So, observed sequences are classified into homogeneous groups (clusters) by applying a clustering method, utilizing principal components calculated for each sequence, as variables characterizing the sequence. Moreover, to determine the sequence pattern most representing of each cluster, a multidimensional normal distribution is fitted to sequence PC data and its density function is estimated. Sequences are ranked by density: those closest to the maximum

[2]In kinematic data analysis, where variables are strongly correleted, the use of more components doesn't help to explain the effect of original variables on the fenomena

[3]The variables mv, mv^2 and mv^3 are strongly correlated each one, and are an expression of the average speed. The correlation ratio are mv/mv^2 97%; mv/mv^3 98%; mv^2/mv^3 92%.

Table 2: Variables characterizing driving behavior

Variable	Component1	Component2	Component3	Component4
Tral (s)	-0.028	-0.145	-0.587	0.147
Dist (m)	0.882	-0.065	0.276	0.052
mv (km/h)	0.922	0.160	0.149	0.041
$mv^2(km^2/h^2)$	0.941	0.104	0.205	-0.021
$mv^3(km^3/h^3)$	0.928	0.058	0.242	-0.017
m_vapos (m^2/s^3)	-0.153	0.291	0.288	0.599
Tseq(s)	0.846	-0.094	0.145	0.075
DS1 (%)	0.343	-0.578	-0.186	0.431
DS2 (%)	0.304	-0.820	-0.166	0.099
DS3 (%)	-0.329	-0.287	0.454	-0.593
DS4 (%)	-0.561	0.484	0.370	0.355
DS5 (%)	0.411	0.612	-0.559	-0.043
DS6 (%)	0.573	0.439	-0.335	-0.301

density (the mode of distribution) are taken as the most representative. Discriminant analysis is applied to outline features and reciprocal differences of clusters. Canonical Discriminant Analysis is used to determine which variables discriminate between clusters (groups) of multivariate observations. Some optimal combinations (functions) of variables are automatically determined so that the first function provides the overall discrimination between groups, the second provides the second most, and so on. Functions are denoted as canonical variables (called in the paper Can1, Can2,..). In figure 4 a cluster representation of sequences is shown. Can 1 sequences are correlated with variables that differentiate the cluster's sequences from slow to fast and long time duration, while Can 2 sequences are correlated to variables that explain the slope variability features.

The selected road test is subdivided in about 39 sequences, that are grouped in five clusters. For each cluster it is possible to point out fundamental differences in the kinematic features. Driving cycles are defined starting from the cluster of sequences which are subsequently grouped into clusters of cycles. The clusters of sequences allow us to construct the criterion for the division of the speed diagram in sections, each one corresponding to a driving cycle. The rule used to define a cycle, defined as the succession of homogeneous sequences, is the following:

I A cycle begins with the first sequence of a trip, or when there is a transition from one group to another, i.e. 1-2, 1-3, 2-3, and vice versa.

II A cycle ends with the last sequence of a journey, or a transition with the previous sequence. In this phase, the construction of new variables characterizing the cycles

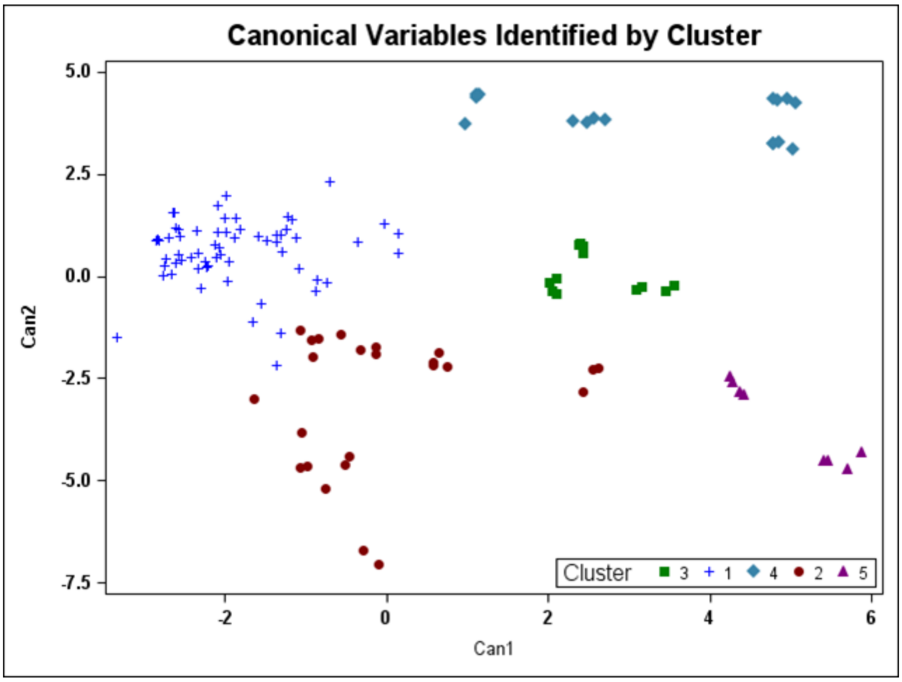

Figure 4: Cluster representation of sequences

in a similar way as done for the sequences is made.

After that, same statistical methodologies (Meccariello et al., 2014), applied on sequences, are carried out to investigate the kinematic characteristics of driving cycles, which are formed by applying the above rule. Clusters of cycles synthesize and represent the different behaviour and traffic situations that have occurred. For this reason, for each driving cycle (statistical unit) the average value of pollutants and fuel consumption are calculated. Results are illustrated by cluster representation in the Can 1, Can 2 scatter plot (figure 5). In table 3 the total canonical structure of the discriminant analysis is shown. These are the correlations between the continuous variables used (Component 1 and Component 2) and the two discriminant functions (Can1 and Can2). We can see that the first discriminant function is positively correlated with F1 and F2; and the second discriminant function is negatively correlated with F1 and positively with F2.

Table 3: Total canonical structure

Variable	Can1	Can2
f1_mean	0.894	-0.446
f2_mean	0.518	0.855

Accordingly to the characteristic of the PC factor, the groups are quite internally

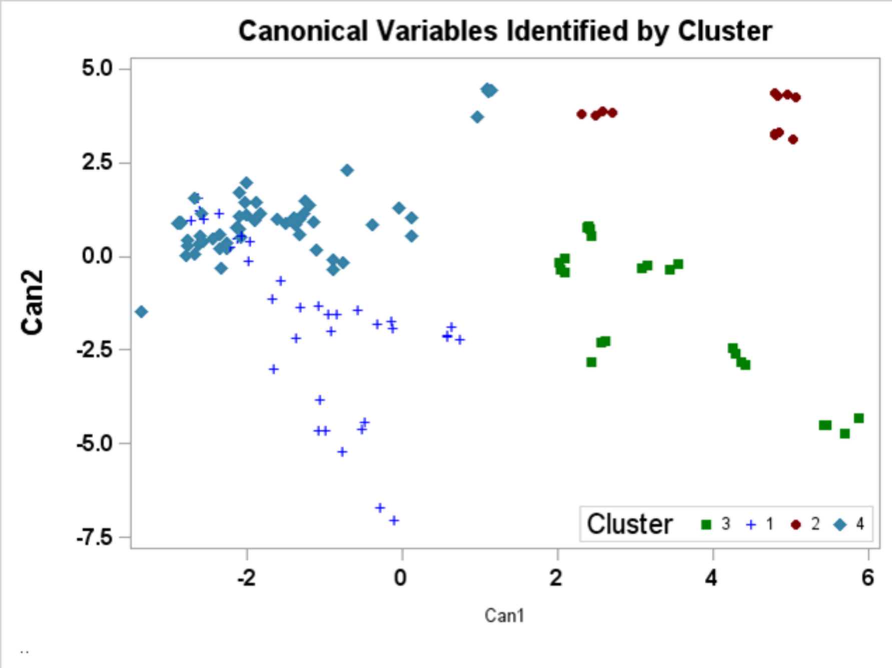

Figure 5: Cluster representation of cycles

homogeneous and differentiated in terms of mean velocity, distance covered and different percentage of DS1-DS3 (representing sequence realized for most of the time in downhill road) and DS4-DS6 (representing sequence realized for most of the time in uphill road).

Table 4: Mean Variables characterizing WMR path

Cluster	mv (km/h)	Tral	Trunning	NSeq	Dist(m)	DS1(%)	DS2(%)	DS3(%)	DS4(%)	DS5(%)	DS6(%)
1	6.73	557	962	34	757.17	7	26	27	28	12	0
2	18.92	123	1238	8	5859.56	0	5	6	19	54	16
3	16.95	85	3170	15	14520.97	9	36	13	23	16	3
4	7.62	414	1088	35	1427.64	0	2	17	54	25	2

The Cluster 1 and 4 have the lowest average speed, while Cluster 2 and 4 correspond to path's segments taken essentially uphill with different percentages of positive slope (DS5 and DS6); they spend 70% and 27%, respectively, in uphill phases. Instead, Cluster 1 and 3 are characterized especially by cycle carried in downhill path; they spend 53% and 48%, respectively, in downhill phases. Moreover, Cluster 1 and 4 have the lowest average speed with higher number of sequences, typical of congest areas.

4 Results and Conclusions

The aims of this activity are to compare fuel consumption and emissions on road during real world experimental tests, in order to identify and characterize representative road routes. Moreover, this paper seeks to give a contribution to on-board measurements with PEMS, in different geographical areas, using statistical methodologies to analyze driving behaviour and perform correlations with emission measurements. In this framework a statistical approach has been proposed capable to consider more attributes than the simple speed to characterize driving behavior. The methodology allows to characterize cars operating conditions in different trip zones and to define clusters of cycle with typical kinematic pattern. In the analysis and definition of clusters for VMR path, slope gradient plays a significant role especially in the return part of the path. In figure 6 the latitude vs longitude of VMR Road acquired on-road and the three times repeated in laboratory WMR_LAB_R1-3, with different colour and label according to the cluster analysis, are shown. Here it is clear that the cluster analysis groups well and summarizes the main features of the kinematics on road. The succession of the same cluster is encountered throughout the path despite small variations kinematic. In fact, the sequences cluster for all path is 3-4-2-4-3-1-4-1-3-1. In addiction, the differences

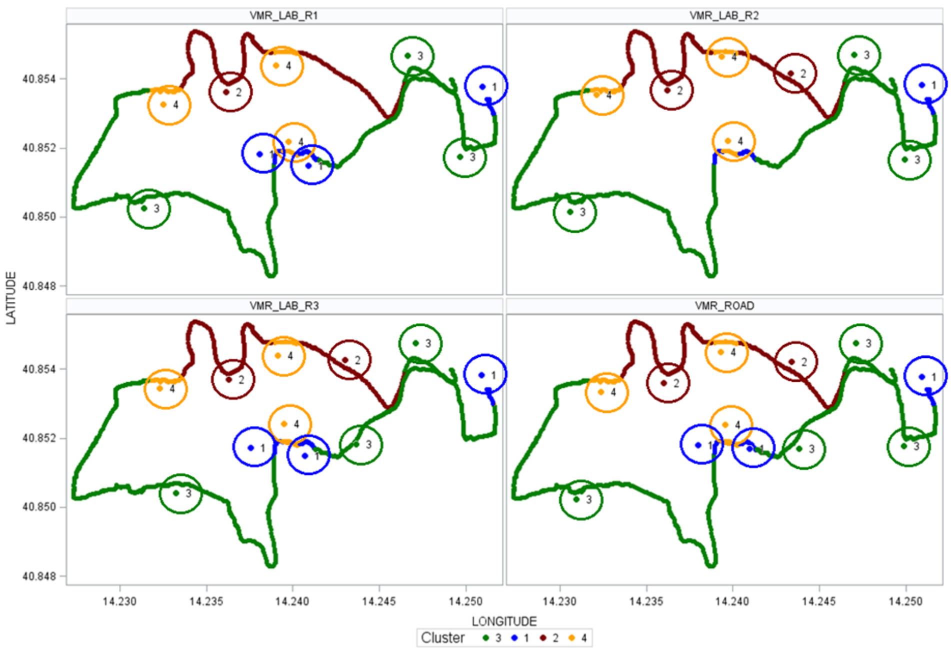

Figure 6: Latitude vs longitude of VMR Road and its three repetition (WMR_LAB_R1-3).

between laboratory and road CO_2 emissions results are presented in the figure 7. In the following plots, LAB variable takes value L for laboratory tests and the value R for on road tests. Also variable CLUSTER, which assumes value 1-4 indicates cycle's data belonging to particular cluster. In according to figure 6, with the same cluster colours and label of figure 7, we can highlight the effects on CO_2 emissions due to the influence of slope variability. This phenomenon is evident not only from a qualitative analysis on the knowledge of the path, but also mainly from the inherent nature of the cluster resulting from the effect of the used variables.

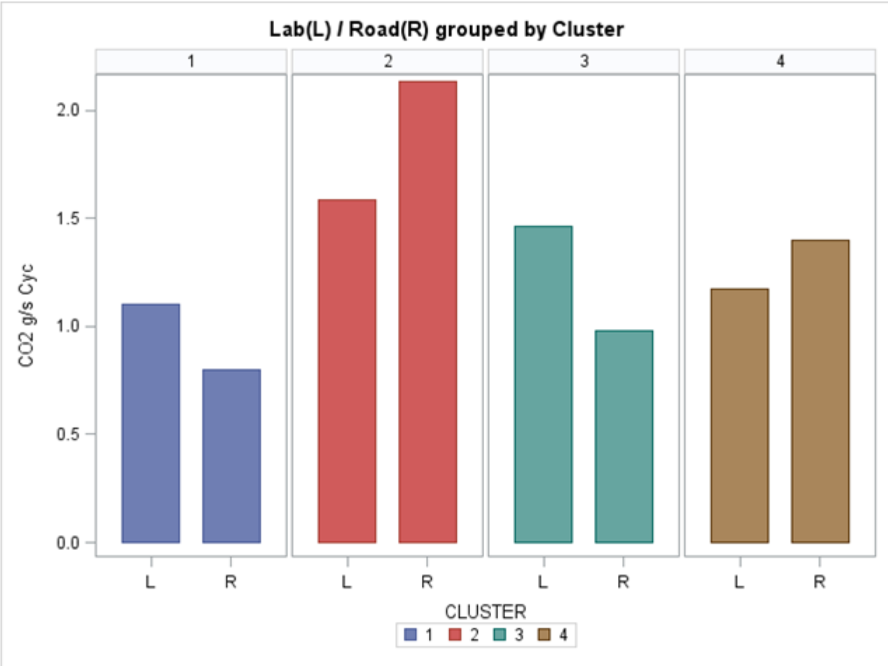

Figure 7: CO_2 cluster mean values lab/road comparison over the path

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