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Using Portable Emission Measurement System to Test Emissions of Light Duty Vehicle on Texas Highways with Different Pavement Roughness

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- Classifying Pavement Roughness Indexes Based on Vehicle Emissions
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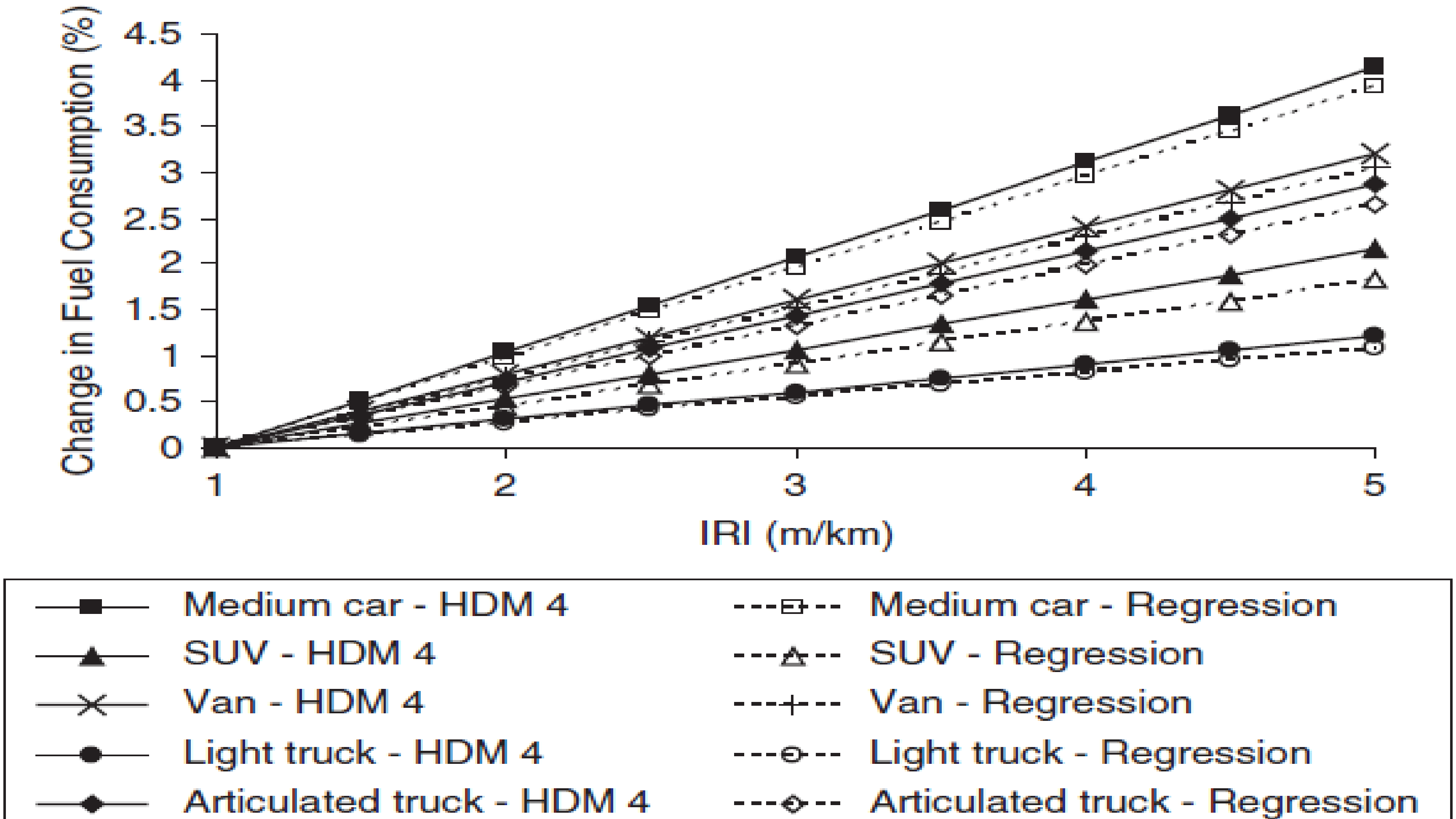
One Example: A Calibrated Model for Estimating Pavement Effect on Fuel Consumption

- By Imen Zaabar and Karim Chatti



Research Questions

- Will Roadway Roughness Really Affect Vehicle Emissions
- What would be the Trend if such Impacts are True?



Methodology

- Test Vehicle Emissions Using PEMS
- Measure Pavement Roughness
  - From a phone application, and/or
  - From DOT measurement record
- Cluster Roughness Based on Pavement Roughness
- Model the Nonlinear Relationships between "Roughness + other Independent Variables" and Vehicle Emissions in Work Zone
  - With serious changes of pavement roughness

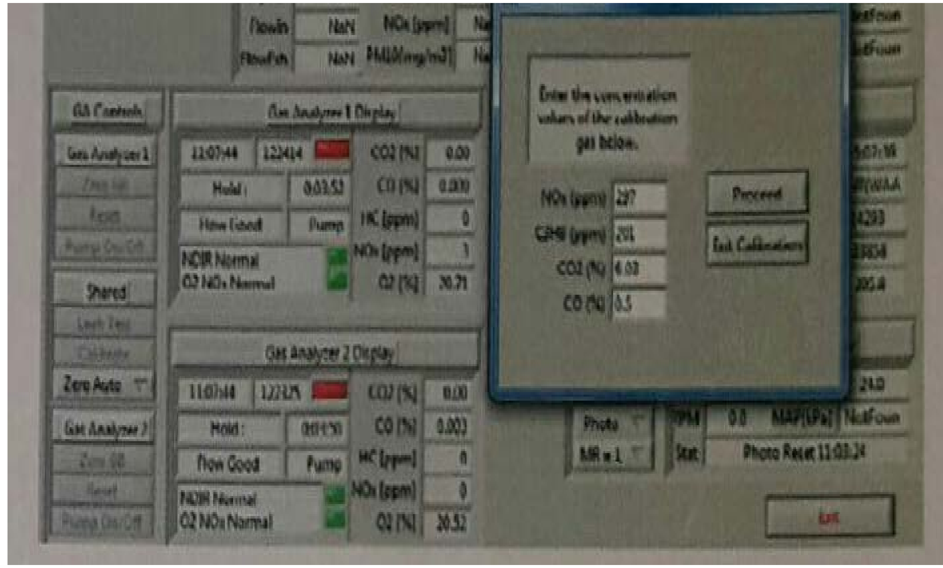
A Dedicated Test Vehicle

- A 2004 Passenger Vehicle
- Starting Mileage 16,496 km

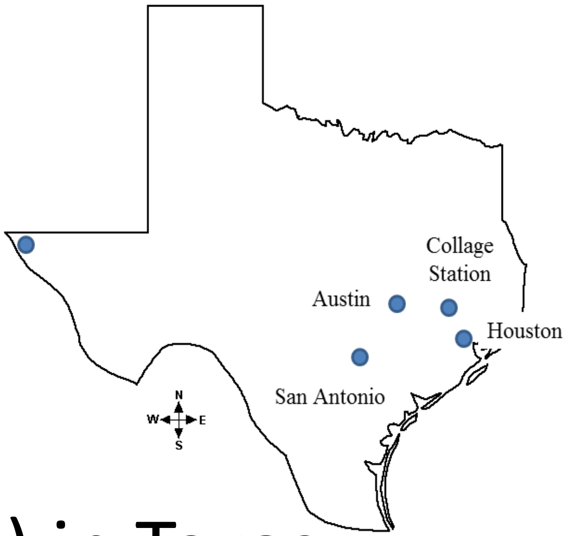
Vehicle Information		Engine Information	
Year	2004	Displacement (L)	2.5
Make	Subaru	Cylinder Configuration	4
Model	Forester	HP@RPM	165 @ 5699
Vehicle Weight	3100 lb	Torque@RPM	225 Nm @ 4000
Test Weight	3500 lb	Fuel Delivery	Gas

PEMS for Testing

- Axion GlobalMRV
- CO, CO_2, NO_x, HC, PM (for HDDV)



Emission Measurement



- Test roads (2,000+ km/ 1,242 mile+) in Texas
- Data Collection
  - Vehicle activity, such as speed, MAP, rpm, Intake Air Temperature (IAT), Ambient Air Temperature (AAT), etc. from OBD II/sensors
  - Vehicle emissions (CO_2, CO, HC, NO_x) and fuel consumption(FC) from Portable Emissions Measurement System (PEMS)
  - Pavement roughness from a smartphone app for every 20 meters

Clustering Pavement Roughness Based on Vehicle Emission

- Data pairs were prepared. Each includes International Roughness Index (IRI), geographic location, emission rates, speed, and engine information.
- Normalization for four emission indexes (CO, CO_2, NO_x, and HC)

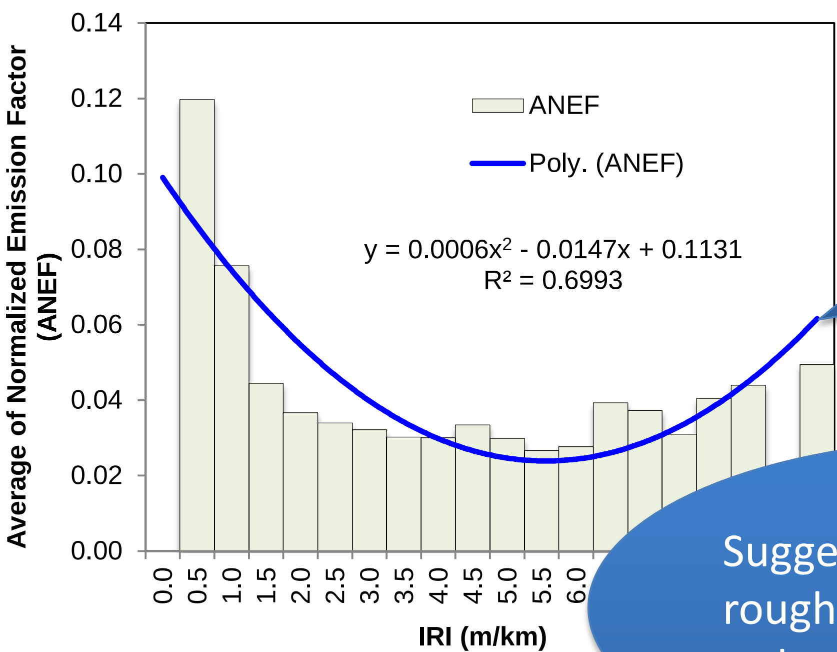
$$x_i' = \frac{x_i - x_{i,min}}{x_{i,max} - x_{i,min}}$$

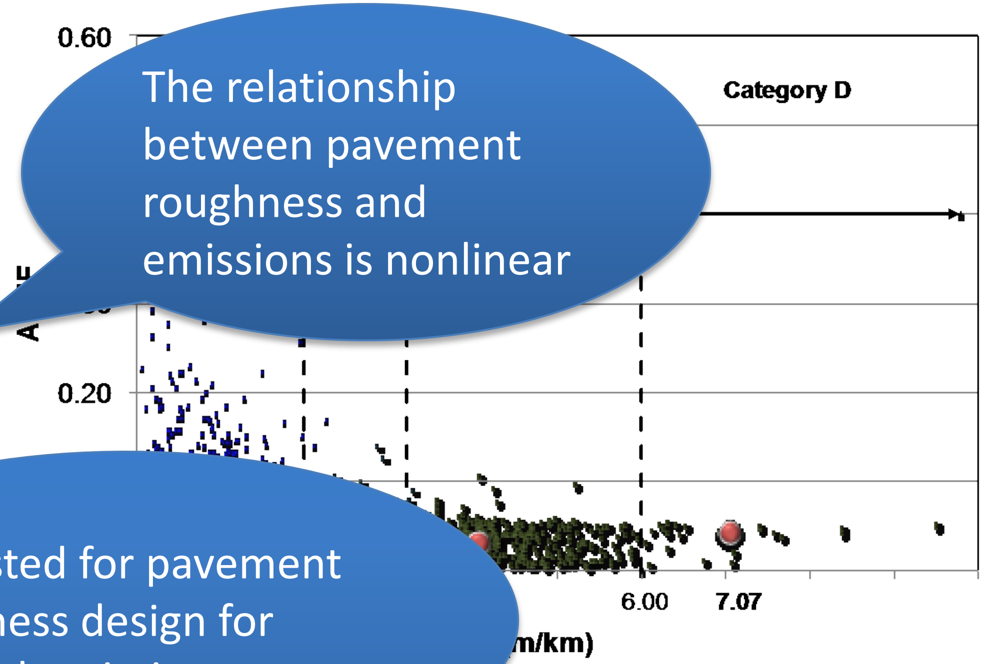
x_i = the interpolated emission factor for emission index i,
$x_{i,min}$ =are the minimum values of all emission factors for emission index i;
$x_{i,max}$ = are the maximum and minimum values of all emission factors for emission index I;
x_i' = the normalized emission factor for emission index i, ranging between 0 and 1.

- Identify a clustering model from three clustering models
  - o TwoStep, Kohonen, and K-means

Clustering Model	Clusters	Silhouette
TwoStep	4	0.576
Kohonen	12	0.552
K-means	5	0.311

Clustering Results





The relationship between pavement roughness and emissions is nonlinear

Suggested for pavement roughness design for reduced emissions

Category	IRI		malized Emission Factor (ANEF)		
	Range	Cluster Ce	Ave.	Std	Evaluation
A	(0.00-1.99]	1.36	0.051	0.055	High
B	(1.99-3.21]	2.54	0.032	0.017	Low
C	(3.21-6.00]	4.07	0.030	0.016	Low
D	> 6.00	7.07	0.039	0.014	High

Findings

Category	IRI				In-vehicle noise	Heart Rate	General Impression
	Range	Ave.	Std.	Evaluate			
A	(0.00-1.99]	0.051	0.055	High	60-70	Low	Poor
B	(1.99-3.21]	0.032	0.017	Low	60-70	Low	Optimal
C	(3.21-6.00]	0.030	0.016	Low	> 70	High	Acceptable
D	> 6.00	0.039	0.014	High	>70	High	Poor

From our another research

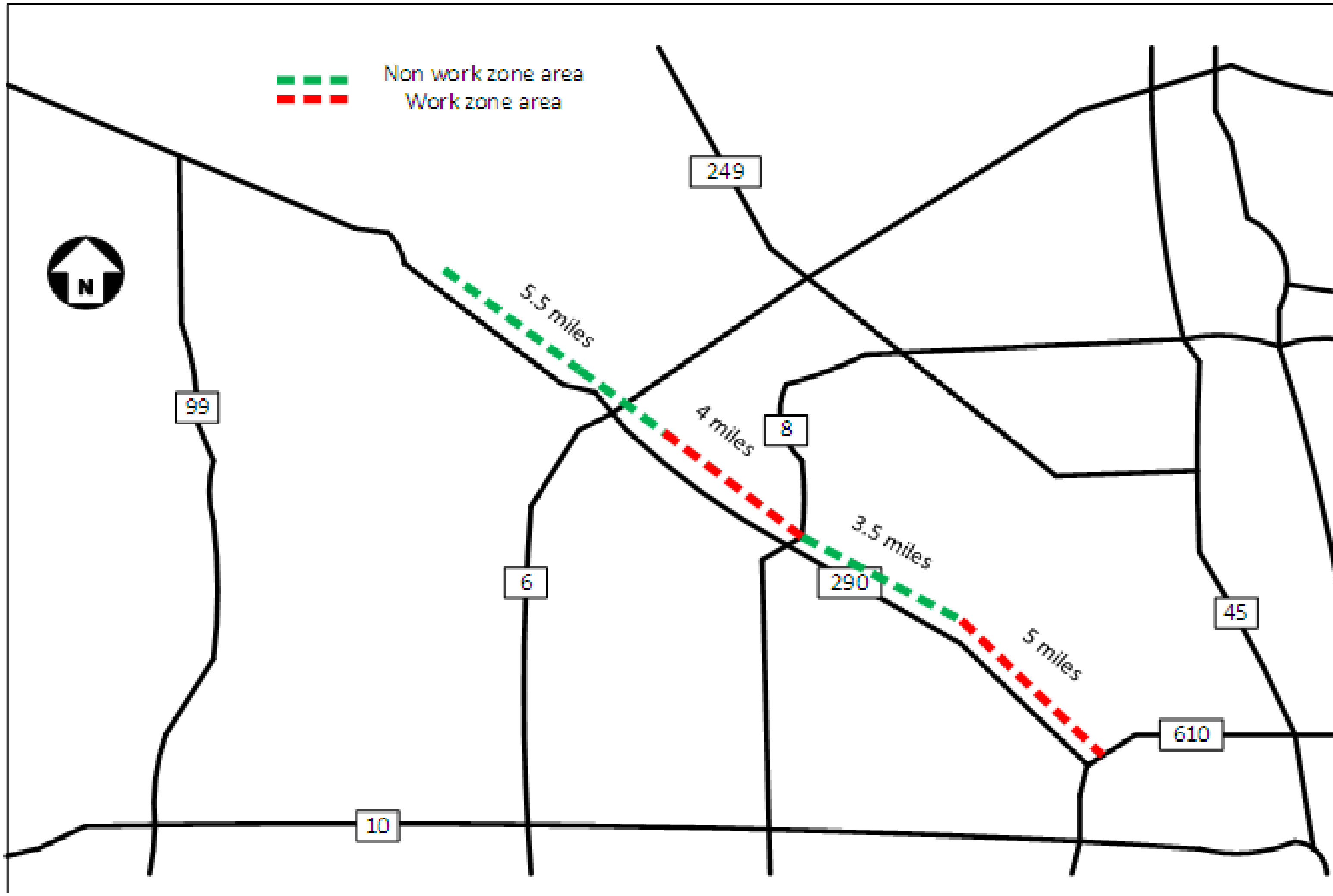
- Category B is Recommended for Pavement Roughness Design
  - Less vehicle emissions
  - High fuel consumption efficiency
  - Lower in-vehicle noise
  - Better riding conform, and
  - Lower possibility of adverse health effects

Evaluation of the Impact of Work Zone on Vehicular Emissions Considering Roughness

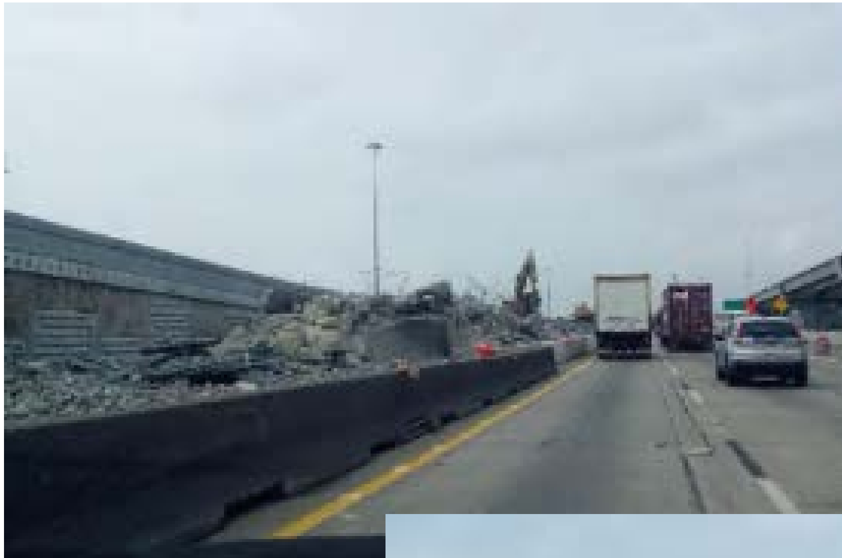
- Investigated the effects of work zone on vehicular emissions in consideration of roadway roughness profiles
- Proposed an emission model based on the operating mode binning method and roughness data to quantify the impact of road roughness on vehicular emissions
- Analyzed roadway construction related emissions

Data Collection

- A Work Zone in US 290 Houston, TX Using PEMS
- 2:30 p.m. to 5 p.m. on March 19, 2015, Dry pavement condition



Test Site

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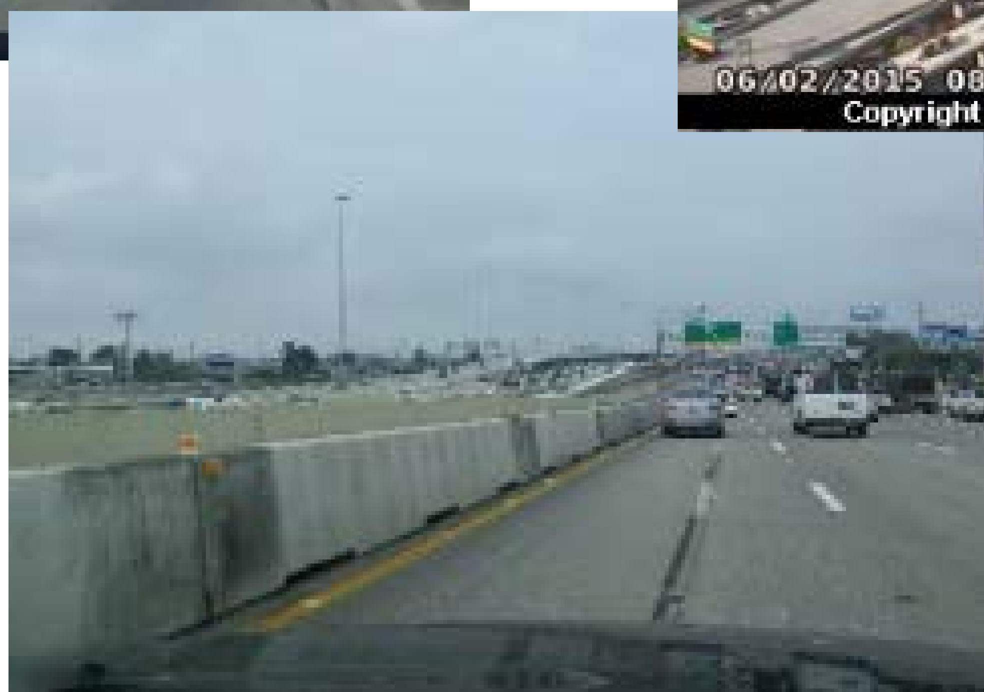


Methodology

- Emission Factor in work zone is a function of emission factor in non-work zone and the roughness under both situations

$$EF_w^i = \beta_1 EF_n^{\beta_2 \frac{IRI_w}{IRI_n} + \beta_3} \quad RMSE_i = \sqrt{\frac{\sum_{t=1}^{n} (EF_{real} - EF_{model})^2}{n}}$$

- Emission factor data pairs in work zone and non-work zone area were compared within each operating mode ID bin, which is based on the values of speed and vehicle specific power (VSP)

Operating Mode Binning and Frequency

OMID	Operating Mode Description	Frequency (0)	Frequency (1)
0	Braking: Acceleration<-2mph/s or<-1mph/s for 3 seconds	360	285
1	Idling: -1≤Speed<1	12	0
11	Low Speed Coasting: VSP<0; 1≤Speed<25	287	267
12	Cruise/Acceleration: 0≤VSP<3; 1≤Speed<25	369	296
13	Cruise/Acceleration: 3≤VSP<6; 1≤Speed<25	228	122
14	Cruise/Acceleration: 6≤VSP<9; 1≤Speed<25	329	245
15	Cruise/Acceleration: 9≤VSP<12; 1≤Speed<25	415	386
16	Cruise/Acceleration: 12≤VSP; 1≤Speed<25	6	24
21	Moderate Speed Coasting: VSP<0; 25≤Speed<50	125	102
22	Cruise/Acceleration: 0≤VSP<3; 25≤Speed<50	282	266
23	Cruise/Acceleration: 3≤VSP<6; 25≤Speed<50	363	360
24	Cruise/Acceleration: 6≤VSP<9; 25≤Speed<50	0	0
25	Cruise/Acceleration: 9≤VSP<12; 25≤Speed<50	341	345
27	Cruise/Acceleration: 12≤VSP<18;25≤Speed<50	317	433
28	Cruise/Acceleration: 18≤VSP<24; 25≤Speed<50	27	12
29	Cruise/Acceleration: 24≤VSP<30; 25≤Speed<50	2	0
30	Cruise/Acceleration: 30≤VSP; 25≤Speed<50	0	0
33	Cruise/Acceleration: VSP<6; 50≤Speed	182	239
35	Cruise/Acceleration: 6≤VSP<12; 50≤Speed	326	373
37	Cruise/Acceleration: 12≤VSP<18; 50≤Speed	190	251
38	Cruise/Acceleration: 18≤VSP<24; 50≤Speed	78	116
39	Cruise/Acceleration: 24≤VSP<30; 50≤Speed	127	145
40	Cruise/Acceleration: 30≤VSP; 50≤Speed	6	1

Lower Speed

Medium Speed

Higher Speed

0 stands for work zone, 1 for non-work zone

Emission Factors

- Work Zone and Non Work Zone

	EF_w	EF_{nw}	$(EF_w-EF_{nw})/EF_{nw}$
CO_2 (g/mi)	0.392	0.340	15.2%
CO (mg/mi)	1.392	1.966	-29.2%
HC (mg/mi)	0.140	0.183	-23.5%
NO_x (mg/mi)	0.158	0.091	73.6%
FC (g/mi)	0.138	0.108	27.8%

Emission, Fuel Consumption and eIRI of Operating Mode Bins

OMID	CO_2 (0)	CO_2 (1)	CO (0)	CO (1)	NO_x (0)	NO_x (1)	HC (0)	HC (1)	FC (0)	FC (1)	eIRI (0)	eIRI (1)
0	0.087	0.073	0.364	0.531	0.028	0.021	0.018	0.012	0.028	0.023	2.172	1.940
11	0.295	0.220	1.364	1.252	0.073	0.045	0.067	0.019	0.094	0.070	1.704	1.584
12	0.527	0.345	4.324	6.111	0.127	0.108	0.090	0.029	0.169	0.112	1.753	1.607
13	0.885	0.552	5.446	8.867	0.221	0.125	0.153	0.093	0.282	0.179	1.928	1.513
14	1.088	0.801	5.502	8.771	0.277	0.188	0.175	0.203	0.347	0.258	1.767	1.641
15	1.264	0.980	2.286	3.551	0.322	0.239	0.180	0.482	0.399	0.311	1.623	1.618
21	0.133	0.128	0.826	0.765	0.034	0.028	0.020	0.016	0.042	0.041	1.794	1.754
22	0.218	0.210	1.122	1.798	0.057	0.046	0.036	0.021	0.069	0.067	1.885	1.760
23	0.303	0.286	1.071	1.803	0.077	0.060	0.043	0.059	0.097	0.091	2.317	1.671
25	0.430	0.447	0.752	1.193	0.105	0.096	0.070	0.064	0.137	0.142	1.995	1.634
27	0.596	0.597	0.815	0.923	0.138	0.129	0.123	0.105	0.182	0.190	1.860	1.808
28	0.760	0.750	0.761	0.461	0.172	0.172	0.127	0.334	0.240	0.237	2.032	2.070
33	0.171	0.189	0.432	1.076	0.045	0.048	0.021	0.035	0.054	0.060	2.072	2.144
35	0.310	0.299	0.592	1.524	0.079	0.076	0.050	0.075	0.098	0.095	2.168	2.021
37	0.415	0.377	0.683	1.426	0.102	0.100	0.068	0.124	0.132	0.120	2.174	1.961
38	0.495	0.423	0.874	1.263	0.119	0.110	0.107	0.135	0.157	0.134	2.231	1.946
39	0.455	0.452	0.907	1.413	0.116	0.123	0.066	0.082	0.144	0.144	1.872	1.566

0 stands for work zone, 1 for non-work zone

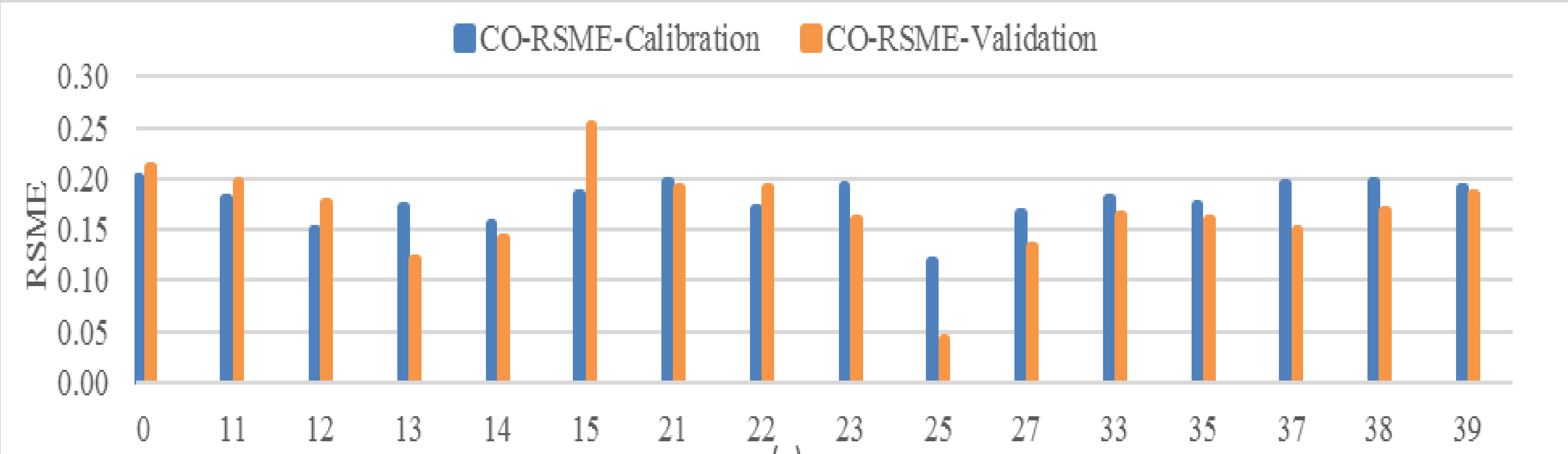
Units: CO_2 (g/mi), CO (mg/mi), NO_x(mg/mi), HC(mg/mi), FC(g/mi)

Calibrated Parameters for Emission Factor under different Operation Mode ID bin

OMID	Index	b1	b2	b3	R^2	RSME
0	FC	0.940	-0.040	0.952	0.929	0.021
	CO_2	0.954	-0.045	1.168	0.890	0.064
	CO	0.634	0.095	0.981	0.917	0.201
	NO_x	0.879	-0.009	0.903	0.930	0.141
	HC	0.262	0.680	1.298	0.801	0.162
11	FC	1.185	-0.062	0.968	0.899	0.062
	CO_2	1.152	-0.054	1.168	0.916	0.073
	CO	0.621	-0.091	0.982	0.927	0.182
	NO_x	0.887	-0.020	0.901	0.931	0.170
	HC	0.261	0.694	1.296	0.792	0.119
12	FC	1.149	-0.055	0.956	0.917	0.012
	CO_2	1.174	-0.064	1.164	0.918	0.022
	CO	0.652	-0.071	1.014	0.949	0.151
	NO_x	0.896	-0.021	0.865	0.919	0.103
	HC	0.245	0.675	1.315	0.822	0.093
	FC	1.164	-0.063	0.982	0.886	0.017
	CO_2	1.171	-0.079	1.151	0.891	0.033
	CO	0.616	-0.068	0.990	0.905	0.173

Comparing of RMSE on Each Operating Mode Bin

- For Work Zone and Non-Work Zone Area
- 70% Used for Modeling, 30% for Validation



(c)

FC-RSME-Calibration
FC-RSME-Validation
RSME
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0 11 12 13 14 15 21 22 23 25 27 33 35 37 38 39
(a)
CO2-RSME-Calibration
CO2-RSME-Validation
RSME
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0 11 12 13 14 15 21 22 23 25 27 33 35 37 38 39
(b)
Nox-RSME-Calibration
Nox-RSME-Validation
RSME
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0 11 12 13 14 15 21 22 23 25 27 33 35 37 38 39
(d)
HC-RSME-Calibration
HC-RSME-Validation
RSME
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0 11 12 13 14 15 21 22 23 25 27 33 35 37 38 39
OMID
(e)

Results

- The calibration and validation results of fuel consumption has the highest average accuracy compared with CO_2, CO, HC and NO_x
- The proposed model has a good fit for NO_x and HC in the relatively higher speed range (above 25 mph) while in the low speed range (OMID between 0 and 13), the error may exceed 0.1 in some cases
- The general trend of this model is that highest accuracy is achieved in the intermediate speed range (OMID between 21 and 27) and in the low speed range the model has highest error

Findings

- Work zone can contribute to significantly increased emission factors of CO_2, NO_x and fuel consumption and reduced emission factor of CO and HC.
- Increased roughness in work zone compared with the same non-work zone roughness leads to increased emission factor for CO_2, NO_x and fuel consumption and the opposite effect can be observed for CO and NO_x
- The results are suggestive of the findings drawn, but more field work needs to be done in the future to see whether the findings are robust to support the conclusion


Thank you!