Chapter 6

Standardization of Vibration Metrics Using PCVE and RVEL

6.1 Preface

While Chapter 5 provided an empirical foundation by analyzing directional and modal vibration characteristics across various speed hump profiles and vehicle classes, the current chapter transitions to a smoother pavement context. This chapter builds upon this by introducing standardized vibration metrics, Reference Vibration Emission Level (RVEL) and Passenger Car Vibration Equivalence (PCVE), based on data collected from straight, hump-free road segments. This shift enables consistent, quantifiable and comparative assessment of vehicle-induced vibrations under uniform surface conditions, establishing a robust baseline for vibration standardization.

This chapter introduces two standardized metrics, Reference Vibration Emission Levels (RVEL) and Passenger Car Vibration Equivalence (PCVE), to quantify and normalize traffic-induced vibrations (TIV) across heterogeneous vehicle classes. RVEL captures the absolute vibration signature of each vehicle type across X, Y and Z axes. At the same time, PCVE expresses these vibrations relative to a passenger car, serving as a vibration equivalence reference akin to PCU in traffic engineering.

The whole experimental framework, including study sites, instrumentation, data acquisition and unified signal preprocessing (FFT filtering, transient removal, energy-based segmentation), is detailed in Section 4.6. The dataset comprises over 9,200 validated single-vehicle pass-by events. Regression modeling estimates RVEL, followed by PCVE derivation through normalized ratios. A GUI-based Python tool has also been developed to facilitate real-time prediction. These metrics enable absolute and relative vibration comparisons, aiding in vehicle classification, infrastructure planning and vibration-sensitive design.

6.2 Results

This section presents the analysis of traffic-induced vibrations based on the frameworks developed in this study: Reference Vibration Emission Levels (RVEL) and Passenger Car Vibration Equivalence (PCVE). The RVEL framework establishes baseline vibration metrics across various vehicle classes, focusing on X (longitudinal), Y (lateral), Z (vertical) and combined XYZ directional metrics. The PCVE framework standardizes these metrics relative to passenger cars, enabling cross-class comparisons. A custom Python-based tool operationalizes these frameworks and is available in the section 6.2.3. The results are presented with comprehensive statistical analyses and visualizations, showcasing key relationships and trends.

6.2.1 Reference Vibration Emission Level

The Reference Vibration Emission Levels (RVEL) framework was employed to quantify and establish baseline vibration metrics across various vehicle classes. This analysis focused on three orthogonal directions i.e. X (longitudinal), Y (lateral) and Z (vertical) as well as a combined XYZ metric to provide a comprehensive overview of vibrational impacts. Regression analyses were conducted to determine the relationship between vehicle speed and vibration intensity for each metric and vehicle class.

6.2.1.1 Directional Vibration Metrics

The RVEL analysis encompasses three directional axes as X, Y and Z as well as a combined XYZ metric. For each vehicle class, regression models were fitted to assess the relationship between vehicle speed and vibration metrics. The regression parameters, including slope, intercept, R^2, Mean Absolute Error (MAE), Root Mean Square Error (RMSE), p-values and F-statistics, are detailed in Tables 6.1, 6.2, 6.3 and 6.4.

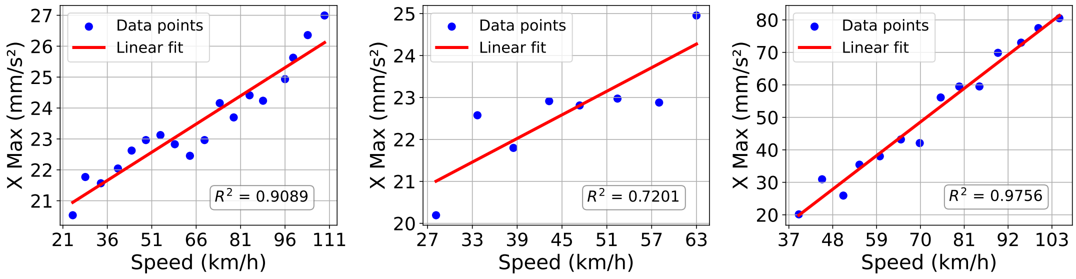
X-Direction Vibration Metrics

The analysis of X-direction (longitudinal) vibration metrics elucidates the relationship between vehicle speed and longitudinal vibration intensity across various vehicle classes. Figure 6.1 illustrates the maximum longitudinal vibrations (X_{Max}) versus speed for each vehicle category, while Table 6.1 presents the corresponding regression parameters.

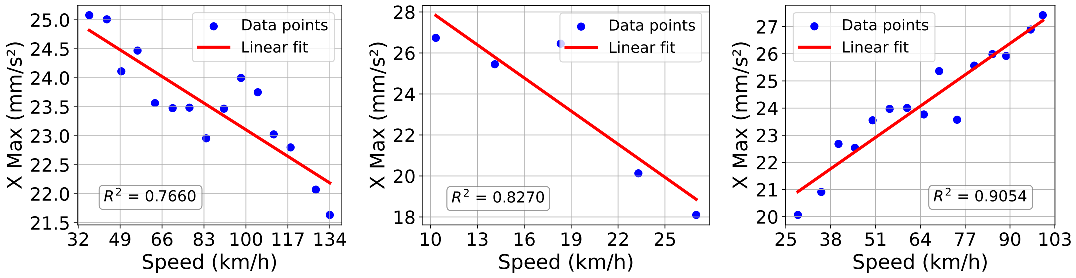
Buses exhibit the most significant positive correlation, with a slope of $0.941\,\text{mm/s}^2/\text{km/h}$ and an R^2 value of 0.976, indicating that speed is a strong predictor of longitudinal vibrations in this class. Similarly, multi-axle trucks (Truck(Tr)) demonstrate a robust relationship, characterized by a slope of $0.371\,\text{mm/s}^2/\text{km/h}$ and an R^2 of 0.960. These high R^2 values suggest that speed accounts for approximately 96% of the variability in longitudinal vibrations for these vehicle types.

In contrast, passenger cars show a modest negative slope of $-0.027\,\text{mm/s}^2/\text{km/h}$ with an R^2 of 0.766, indicating a weaker and slightly inverse relationship between speed and longitudinal vibrations. Light Commercial Vehicles (LCV) present a moderate positive slope of 0.089 mm/s^2/km/h and an R^2 of 0.905, reflecting a significant but less intense correlation compared to buses and multi-axle trucks.

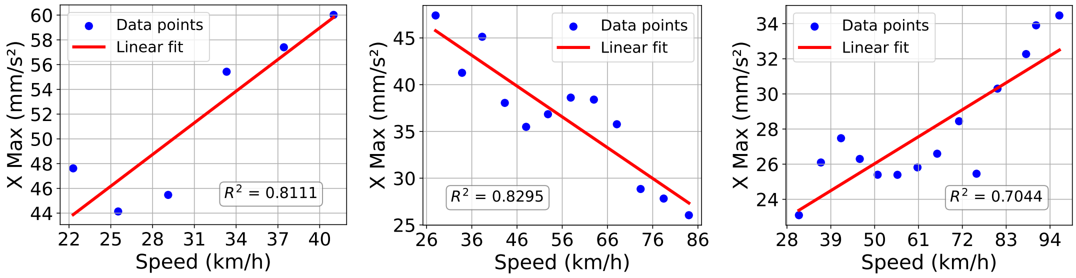
Notably, Truck(Ta) displays an anomalous negative slope of -0.043 mm/s^2/km/h with a low R^2 of 0.082, suggesting that factors other than speed may influence longitudinal vibrations in this category. E-Rickshaws also exhibit a pronounced negative slope of -0.538 mm/s^2/km/h with an R^2 of 0.827, indicating a significant decrease in longitudinal vibrations with increasing speed, potentially due to stabilization mechanisms at higher velocities.



(a) 2-Wheeler (b) 3-Wheeler (c) Bus



(d) Car (e) E-Rickshaw (f) LCV



(g) Tractor(WT) (h) Truck(Ma) (i) Truck(S)

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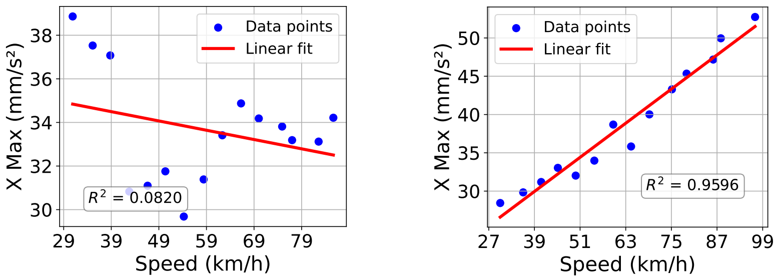
Figure 6.1 continued from previous page



(j) Truck(Ta) (k) Truck(Tr)

Fig. 6.1 X Direction (Max): Vibration Metrics for All Vehicles vs Speed.

Table 6.1 X Metrics

Vehicle	**Metric**	**Slope**	**Intercept**	**R^2**	**MAE**	**RMSE**	**P-Value**	**F-Statistic**
2-Wheeler	X Max	0.061	19.468	0.909	0.438	0.501	9.718e-10	159.633
2-Wheeler	X RMS	0.017	3.101	0.915	0.103	0.131	5.532e-10	172.378
2-Wheeler	X Avg. Power	0.119	28.118	0.875	0.849	1.165	1.215e-08	112.343
Truck(Ta)	X Max	-0.043	36.158	0.082	2.048	2.418	3.009e-01	1.161
Truck(Ta)	X RMS	-0.026	9.214	0.189	0.791	0.926	1.049e-01	3.038
Truck(Ta)	X Avg. Power	-0.233	81.415	0.189	6.996	8.190	1.055e-01	3.027
Truck(S)	X Max	0.140	19.049	0.704	1.499	1.826	1.744e-04	28.591
Truck(S)	X RMS	-0.023	6.784	0.682	0.268	0.321	2.713e-04	25.792
Truck(S)	X Avg. Power	-0.201	59.674	0.673	2.369	2.834	3.245e-04	24.715
LCV	X Max	0.089	18.390	0.905	0.493	0.620	4.988e-08	124.447
LCV	X RMS	0.017	3.449	0.896	0.099	0.128	9.334e-08	111.905
LCV	X Avg. Power	0.153	30.082	0.878	0.840	1.229	2.639e-07	93.588

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Table 6.1 continued from previous page

Vehicle	Metric	Slope	Intercept	R^2	MAE	RMSE	P-Value	F-Statistic
Car	X Max	-0.027	25.805	0.766	0.395	0.449	1.933e-05	42.549
Car	X RMS	-0.003	4.505	0.810	0.043	0.051	4.862e-06	55.443
Car	X Avg. Power	-0.051	40.516	0.890	0.431	0.538	1.356e-07	104.984
Truck(Ma)	X Max	-0.329	54.989	0.829	2.397	2.588	3.833e-05	48.639
Truck(Ma)	X RMS	-0.157	18.458	0.836	0.971	1.204	3.163e-05	50.901
Truck(Ma)	X Avg. Power	-1.433	165.124	0.843	8.767	10.704	2.485e-05	53.864
Truck(Tr)	X Max	0.371	15.462	0.960	1.259	1.528	9.921e-10	285.339
Truck(Tr)	X RMS	0.111	2.633	0.958	0.412	0.465	1.252e-09	274.054
Truck(Tr)	X Avg. Power	0.895	27.831	0.969	2.739	3.189	1.872e-10	380.321
Bus	X Max	0.941	-17.290	0.976	2.333	2.988	4.840e-11	479.320
Bus	X RMS	0.222	-4.382	0.973	0.591	0.749	9.808e-11	424.853
Bus	X Avg. Power	2.061	-45.813	0.980	4.270	5.911	1.458e-11	587.855
3-Wheeler	X Max	0.094	18.364	0.720	0.556	0.657	7.726e-03	15.433
3-Wheeler	X RMS	-0.016	4.901	0.839	0.066	0.080	1.394e-03	31.248
3-Wheeler	X Avg. Power	-0.172	43.889	0.920	0.458	0.568	1.634e-04	69.245
Tractor(WT)	X Max	0.853	24.866	0.811	2.239	2.680	1.433e-02	17.176
Tractor(WT)	X RMS	0.373	3.408	0.783	1.075	1.280	1.914e-02	14.424
Tractor(WT)	X Avg. Power	2.992	37.907	0.761	9.147	10.910	2.330e-02	12.770
E-Rickshaw	X Max	-0.538	33.399	0.827	1.170	1.481	3.228e-02	14.346
E-Rickshaw	X RMS	-0.120	7.264	0.792	0.283	0.370	4.302e-02	11.439
E-Rickshaw	X Avg. Power	-1.978	76.485	0.820	4.337	5.584	3.450e-02	13.622

Validation of X-Direction Regression Models: The regression models for X-direction vibration metrics were validated using Root Mean Square Error (RMSE), p-values, F-statistics and the coefficient of determination (R^2). For example, the model for buses using the X Max metric yielded an R^2 of 0.976 and an RMSE of 2.988 mm/s^2, with a p-value < 0.001 and an F-statistic of 479.32. Similarly, the X RMS model for buses achieved an R^2 of 0.973 and an RMSE of 0.749 mm/s^2, while the model based on X Avg. Power resulted in an R^2 of 0.980 and an RMSE of 5.911 mm/s^2. Additionally, the X Max model for tridem-axle trucks (Truck(Tr)) exhibited an R^2 of 0.960 and an RMSE of 1.528 mm/s^2, with a p-value < 0.001 and an F-statistic of 285.34. These validation metrics affirm that the regression models across X-direction metrics are statistically robust and demonstrate high predictive accuracy in capturing the relationship between vehicle speed and longitudinal vibrations..

Y-Direction Vibration Metrics

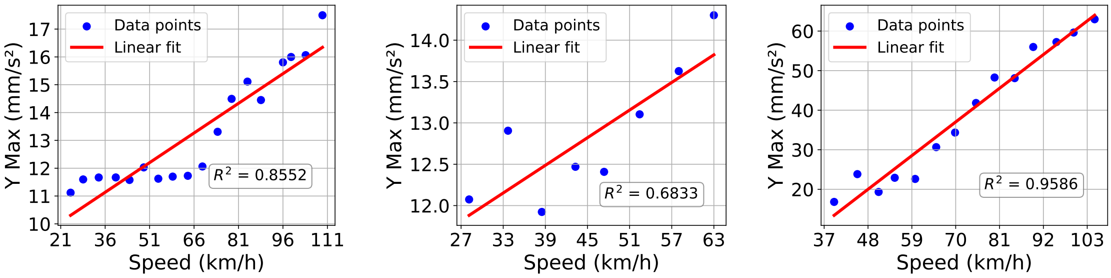
The Y-direction (lateral) vibration metrics measure how speed influences lateral oscillations across diverse vehicle categories. Fig. 6.2 provides an overview of the maximum lateral vibrations (Y_{Max}) as a function of speed, while Table 6.2 presents corresponding regression parameters.

Buses exhibit the highest positive correlation, with a slope of $0.774\,\text{mm/s}^2/\text{km/h}$ and R^2 is 0.959, indicating that speed explains most of the observed variations in lateral vibration for this vehicle class. Truck tridem axle (Truck(Tr)) follow closely, featuring a slope of $0.231\,\text{mm/s}^2/\text{km/h}$ and R^2 is 0.964, underscoring how heavily loaded configurations can substantially intensify lateral oscillations.

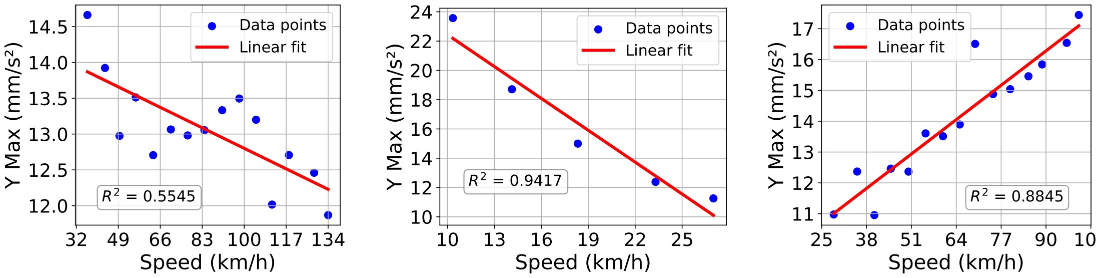
Passenger cars, in contrast, display a modest negative slope of $-0.017\,\text{mm/s}^2/\text{km/h}$ and R^2 is 0.555, implying a weaker and slightly inverse relationship between speed and lateral vibration amplitude. Light Commercial Vehicles (LCV) exhibit a positive slope of

$0.086\,\text{mm/s}^2/\text{km/h}$ and R^2 is 0.885, placing their lateral vibration characteristics between lighter passenger cars and heavier trucks.

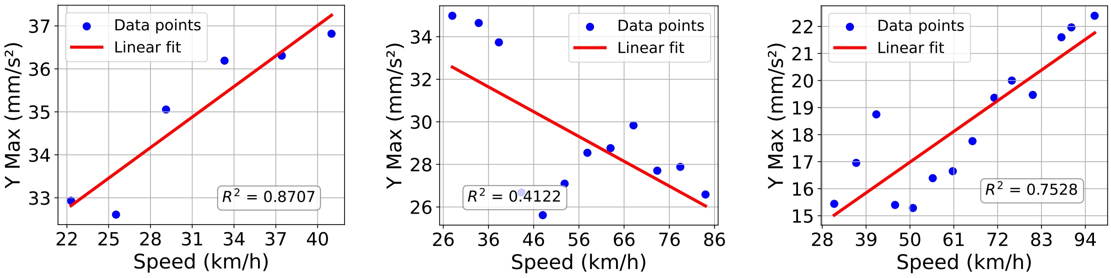
Interestingly, Truck(Ta) shows a positive slope of $0.023\,\text{mm/s}^2/\text{km/h}$ but a low R^2 of 0.050, suggesting that parameters beyond speed such as load imbalance or suspension condition may strongly affect lateral vibrations in that category. Conversely, E-Rickshaws exhibit a pronounced negative slope of $-0.725\,\text{mm/s}^2/\text{km/h}$ and R^2 is 0.942, signifying a marked decrease in lateral vibrations at higher speeds, likely due to their relatively low mass and stabilizing design features.



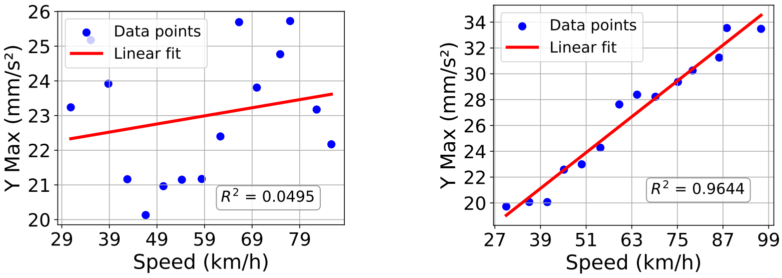
(a) 2-Wheeler (b) 3-Wheeler (c) Bus



(d) Car (e) E-Rickshaw (f) LCV



(g) Tractor(WT) (h) Truck(Ma) (i) Truck(S)



(j) Truck(Ta) (k) Truck(Tr)

Fig. 6.2 Y Direction (Max): Vibration Metrics for All Vehicles vs Speed.

Table 6.2 Y Metrics

Vehicle	Metric	Slope	Intercept	R^2	MAE	RMSE	P-Value	F-Statistic
2-Wheeler	Y Max	0.071	8.577	0.855	0.639	0.760	4.076e-08	94.465
2-Wheeler	Y RMS	0.020	2.237	0.890	0.152	0.186	4.374e-09	129.692
2-Wheeler	Y Avg. Power	0.173	19.564	0.856	1.501	1.846	3.830e-08	95.320
Truck(Ta)	Y Max	0.023	21.610	0.050	1.581	1.738	4.252e-01	0.678
Truck(Ta)	Y RMS	-0.031	7.750	0.465	0.464	0.555	5.126e-03	11.287
Truck(Ta)	Y Avg. Power	-0.269	68.479	0.464	4.107	4.909	5.193e-03	11.241
Truck(S)	Y Max	0.103	11.825	0.753	1.018	1.194	5.799e-05	36.547
Truck(S)	Y RMS	-0.017	5.505	0.462	0.269	0.363	7.518e-03	10.292
Truck(S)	Y Avg. Power	-0.161	49.280	0.473	2.927	3.432	6.557e-03	10.771
LCV	Y Max	0.086	8.563	0.885	0.463	0.670	1.845e-07	99.566
LCV	Y RMS	0.018	2.572	0.892	0.114	0.137	1.199e-07	107.225
LCV	Y Avg. Power	0.140	23.243	0.891	0.801	1.054	1.229e-07	106.771
Car	Y Max	-0.017	14.483	0.555	0.378	0.454	1.449e-03	16.182
Car	Y RMS	-0.004	3.755	0.745	0.065	0.077	3.383e-05	38.056
Car	Y Avg. Power	-0.035	32.330	0.800	0.477	0.528	6.745e-06	52.131
Truck(Ma)	Y Max	-0.117	35.835	0.412	1.977	2.413	2.439e-02	7.013
Truck(Ma)	Y RMS	-0.108	13.953	0.803	0.802	0.929	7.971e-05	40.785
Truck(Ma)	Y Avg. Power	-0.982	124.370	0.815	6.877	8.120	5.865e-05	43.937
Truck(Tr)	Y Max	0.231	12.104	0.964	0.714	0.892	4.702e-10	324.623
Truck(Tr)	Y RMS	0.044	4.223	0.944	0.187	0.215	6.895e-09	203.484
Truck(Tr)	Y Avg. Power	0.545	27.824	0.977	1.372	1.693	3.800e-11	499.492

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Table 6.2 continued from previous page

Vehicle	Metric	Slope	Intercept	R^2	MAE	RMSE	P-Value	F-Statistic
Bus	Y Max	0.774	-17.162	0.959	2.626	3.230	1.161e-09	277.651
Bus	Y RMS	0.197	-4.747	0.972	0.512	0.674	1.156e-10	413.068
Bus	Y Avg. Power	1.672	-39.067	0.969	4.947	5.969	1.903e-10	379.239
3-Wheeler	Y Max	0.056	10.315	0.683	0.367	0.426	1.139e-02	12.946
3-Wheeler	Y RMS	-0.011	3.795	0.825	0.045	0.056	1.792e-03	28.321
3-Wheeler	Y Avg. Power	-0.155	35.434	0.919	0.381	0.517	1.726e-04	67.900
Tractor(WT)	Y Max	0.237	27.532	0.871	0.500	0.595	6.557e-03	26.945
Tractor(WT)	Y RMS	0.098	7.412	0.941	0.145	0.160	1.337e-03	63.672
Tractor(WT)	Y Avg. Power	0.863	65.541	0.941	1.274	1.409	1.338e-03	63.647
E-Rickshaw	Y Max	-0.725	29.684	0.942	1.015	1.086	6.088e-03	48.424
E-Rickshaw	Y RMS	-0.291	9.896	0.971	0.273	0.305	2.154e-03	99.197
E-Rickshaw	Y Avg. Power	-2.498	86.275	0.967	2.567	2.785	2.596e-03	87.311

Validation of Y-Direction Regression Models: The regression models for Y-direction vibration metrics were evaluated using the coefficient of determination (R^2), Root Mean Square Error (RMSE), p-values and F-statistics. For instance, the bus model based on the Y Max metric yielded an R^2 of 0.959 and an RMSE of 3.230 mm/s^2, with a p-value < 0.001 and an F-statistic of 277.651. In contrast, the Y Max model for tridem-axle trucks (Truck(Tr)) exhibited an R^2 of 0.964 and an RMSE of 0.892 mm/s^2, with a p-value < 0.001 and an F-statistic of 324.623. Additionally, models based on Y RMS and Y Avg. Power metrics consistently achieved R^2 values above 0.85 and maintained low RMSEs across vehicle classes. Collectively, these findings confirm that the Y-direction regression models are statistically robust and provide high predictive accuracy for quantifying lateral vibration as a function of vehicle speed.

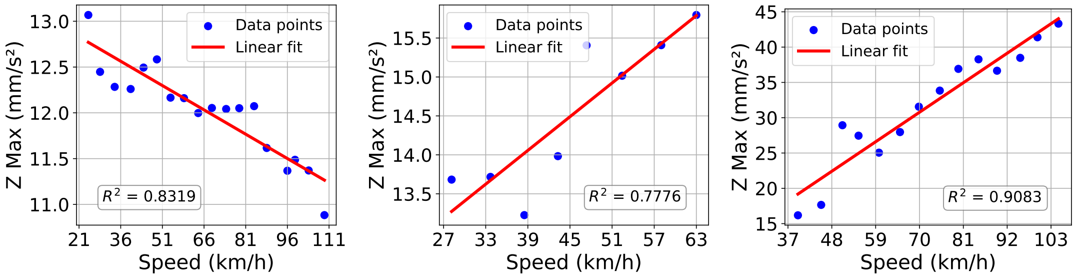
Z-Direction Vibration Metrics

The Z-direction (vertical) vibration metrics reveal how vehicle speed affects the vertical oscillations observed across various vehicle classes. Fig. 6.3 illustrates the maximum vertical vibrations (Z_{Max}) in relation to speed, whereas Table 6.3 lists the corresponding regression parameters.

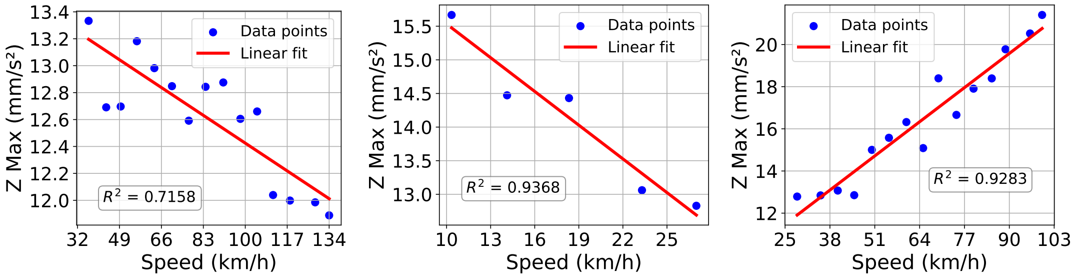
Buses exhibit a pronounced positive correlation, characterized by a slope of 0.380 mm/s^2/km/h and R^2 is 0.908. This suggests that vehicle speed is a strong predictor of vertical vibration magnitudes for buses. Similarly, tridem-axle trucks (Truck(Tr)) show a slope of 0.355 mm/s^2/km/h and R^2 is 0.969, indicating that over 96% of their vertical vibration variability can be attributed to speed.

By contrast, passenger cars register a modest negative slope of -0.012 mm/s^2/km/h and R^2 is 0.716, signifying a weaker and slightly inverse relationship between speed and vertical oscillations. Light Commercial Vehicles (LCV) present a moderate positive slope of 0.125 mm/s^2/km/h and R^2 is 0.928, implying a significant though less intense correlation compared to buses and multi-axle trucks.

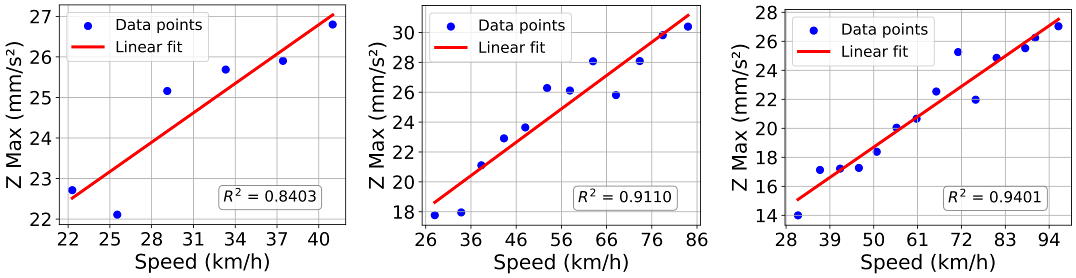
Notably, Truck(Ta) exhibits a positive slope of 0.247 mm/s^2/km/h with R^2 of 0.966, suggesting that speed reliably predicts vertical vibrations in this category. In contrast, E-Rickshaws reveal a pronounced negative slope of -0.167 mm/s^2/km/h and R^2 is 0.937, indicating a marked decrease in vertical oscillations at higher speeds, likely stemming from their lighter mass and stabilizing design.



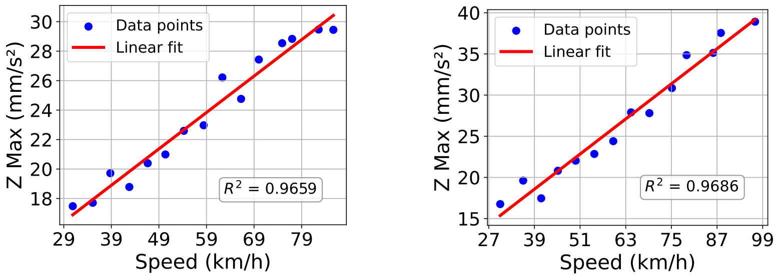
(a) 2-Wheeler (b) 3-Wheeler (c) Bus



(d) Car (e) E-Rickshaw (f) LCV



(g) Tractor(WT) (h) Truck(Ma) (i) Truck(S)



(j) Truck(Ta) (k) Truck(Tr)

Fig. 6.3 Z Direction (Max): Vibration Metrics for All Vehicles vs Speed.

Table 6.3 Z Metrics

Vehicle	Metric	Slope	Intercept	R^2	MAE	RMSE	P-Value	F-Statistic
2-Wheeler	Z Max	-0.018	13.201	0.832	0.165	0.207	1.359e-07	79.172
2-Wheeler	Z RMS	-0.002	3.349	0.781	0.024	0.030	1.159e-06	57.054
2-Wheeler	Z Avg. Power	-0.062	31.334	0.816	0.564	0.765	2.872e-07	70.766
Truck(Ta)	Z Max	0.247	9.259	0.966	0.695	0.787	6.402e-11	368.191
Truck(Ta)	Z RMS	0.058	2.616	0.952	0.194	0.221	5.875e-10	258.302
Truck(Ta)	Z Avg. Power	0.550	21.493	0.944	2.055	2.270	1.609e-09	219.479
Truck(S)	Z Max	0.190	9.193	0.940	0.717	0.969	1.067e-08	188.408
Truck(S)	Z RMS	0.049	2.226	0.968	0.124	0.177	2.250e-10	368.492
Truck(S)	Z Avg. Power	0.363	22.912	0.937	1.455	1.899	1.445e-08	178.590
LCV	Z Max	0.125	8.355	0.928	0.630	0.749	8.172e-09	168.253
LCV	Z RMS	0.017	2.922	0.923	0.080	0.104	1.262e-08	156.586
LCV	Z Avg. Power	0.157	24.891	0.919	0.832	1.010	1.849e-08	146.961
Car	Z Max	-0.012	13.639	0.716	0.206	0.230	7.036e-05	32.736
Car	Z RMS	-0.002	3.494	0.773	0.026	0.032	1.590e-05	44.211
Car	Z Avg. Power	-0.026	30.768	0.841	0.281	0.345	1.534e-06	68.536
Truck(Ma)	Z Max	0.223	12.379	0.911	1.019	1.210	1.431e-06	102.310
Truck(Ma)	Z RMS	0.060	3.248	0.954	0.196	0.225	4.906e-08	209.659
Truck(Ma)	Z Avg. Power	0.610	24.773	0.977	1.296	1.640	1.769e-09	416.141
Truck(Tr)	Z Max	0.355	4.709	0.969	1.066	1.283	2.191e-10	370.195
Truck(Tr)	Z RMS	0.064	2.541	0.965	0.192	0.243	4.290e-10	329.800
Truck(Tr)	Z Avg. Power	0.672	15.403	0.987	1.236	1.555	1.158e-12	902.533

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Table 6.3 continued from previous page

Vehicle	Metric	Slope	Intercept	R^2	MAE	RMSE	P-Value	F-Statistic
Bus	Z Max	0.380	4.180	0.908	2.042	2.423	1.398e-07	118.858
Bus	Z RMS	0.085	0.986	0.980	0.202	0.246	1.548e-11	581.954
Bus	Z Avg. Power	0.764	7.458	0.983	1.451	1.988	4.610e-12	714.608
3-Wheeler	Z Max	0.072	11.243	0.778	0.301	0.433	3.771e-03	20.975
3-Wheeler	Z RMS	-0.012	4.139	0.658	0.086	0.095	1.453e-02	11.546
3-Wheeler	Z Avg. Power	-0.160	38.388	0.695	1.029	1.193	1.013e-02	13.663
Tractor(WT)	Z Max	0.242	17.130	0.840	0.565	0.686	1.013e-02	21.045
Tractor(WT)	Z RMS	0.056	4.677	0.832	0.134	0.165	1.126e-02	19.789
Tractor(WT)	Z Avg. Power	0.538	40.218	0.844	1.308	1.508	9.662e-03	21.622
E-Rickshaw	Z Max	-0.167	17.205	0.937	0.248	0.261	6.870e-03	44.495
E-Rickshaw	Z RMS	-0.049	4.591	0.881	0.100	0.109	1.818e-02	22.127
E-Rickshaw	Z Avg. Power	-0.315	38.816	0.917	0.425	0.571	1.049e-02	32.971

Validation of Z-Direction Regression Models: The Z-direction regression models were evaluated using the coefficient of determination (R^2), Root Mean Square Error (RMSE), p-values and F-statistics. For instance, the bus model based on the Z Avg. Power metric achieved an R^2 of 0.983 and an RMSE of 1.988 mm/s^2, with a p-value < 0.001 and an F-statistic of 714.61. Similarly, the Z Max model for tridem-axle trucks (Truck(Tr)) exhibited an R^2 of 0.969 and an RMSE of 1.283 mm/s^2, with a p-value < 0.001 and an F-statistic of 370.20. Additionally, the models based on Z RMS consistently demonstrated high R^2 values and low RMSE across the vehicle types considered. Collectively, these validation metrics confirm that the Z-direction regression models are statistically robust and provide high predictive accuracy in modeling vertical vibration behavior as a function of vehicle speed.

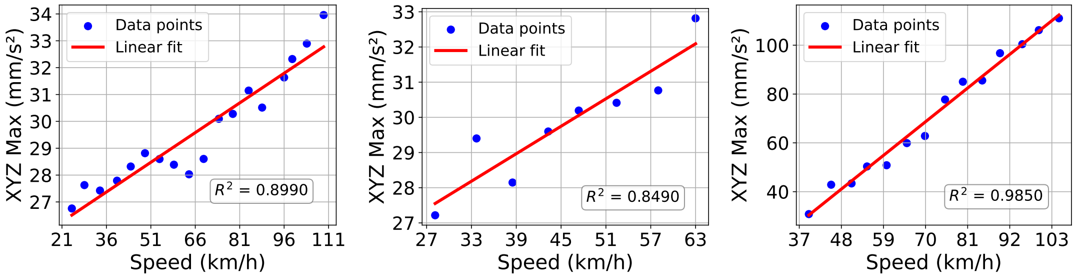
XYZ-Combined Vibration Metrics

The analysis of XYZ-direction (combined) vibration metrics captures how vehicle speed influences the overall three-axis vibration intensity for various vehicle classes. Fig. 6.4 shows the maximum combined vibrations (XYZ_{Max}) in relation to speed, whereas Table 6.4 provides the corresponding regression parameters.

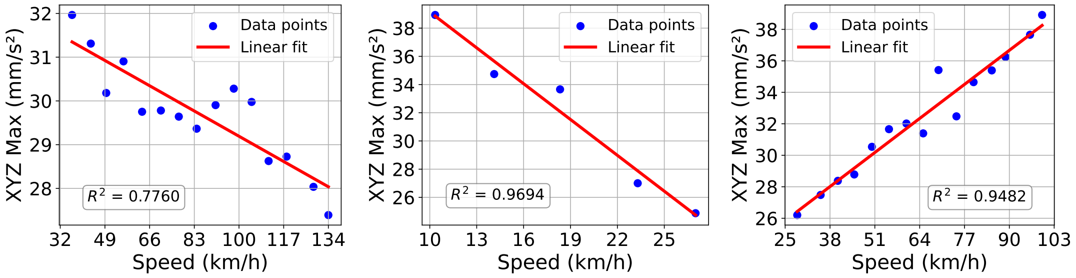
Buses exhibit the strongest positive correlation in the combined XYZ direction, with a slope of $1.254\,\text{mm/s}^2/\text{km/h}$ and an R^2 value of 0.985, indicating that speed is a major predictor of overall vibration levels. Similarly, multi-axle trucks (Truck(Tr)) show a slope of $0.556\,\text{mm/s}^2/\text{km/h}$ and an R^2 value of 0.981, implying that approximately 98% of the variability in their three-dimensional vibration is speed-related.

Light Commercial Vehicles (LCV) present a moderate positive slope $0.166\,\text{mm/s}^2/\text{km/h}$ with an R^2 value of 0.948, denoting a significant yet relatively less pronounced correlation compared to buses and multi-axle trucks. Conversely, passenger cars display a slight negative slope $-0.034\,\text{mm/s}^2/\text{km/h}$ with an R^2 value of 0.776, suggesting a weaker, marginally inverse relationship between speed and combined vibration.

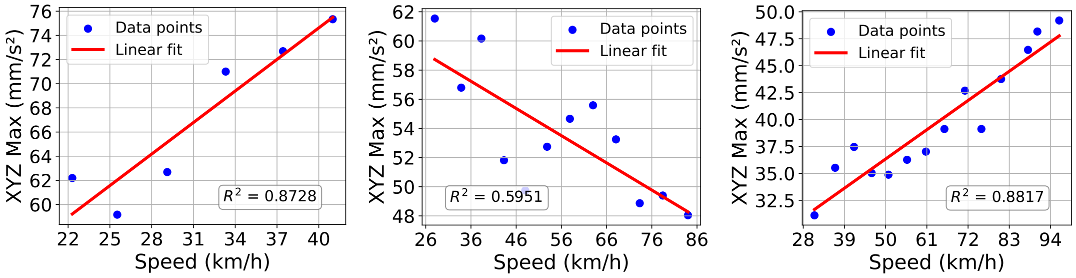
Notably, Truck(Ta) exhibits a positive slope of $0.101\,\text{mm/s}^2/\text{km/h}$ but a low R^2 value of 0.279, indicating that other factors besides speed likely govern overall vibrations in this category. By contrast, E-Rickshaws display a marked negative slope $-0.847\,\text{mm/s}^2/\text{km/h}$ with an R^2 value of 0.969, pointing to a substantial reduction in three-axis vibration as speed increases, possibly attributable to lightweight construction and stabilizing design features.



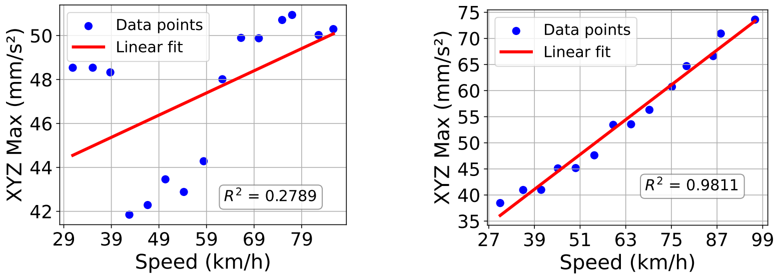
(a) 2-Wheeler (b) 3-Wheeler (c) Bus



(d) Car (e) E-Rickshaw (f) LCV



(g) Tractor(WT) (h) Truck(Ma) (i) Truck(S)



(j) Truck(Ta) (k) Truck(Tr)

Fig. 6.4 XYZ Direction (Max): Vibration Metrics for All Vehicles vs Speed.

Table 6.4 XYZ Metrics

Vehicle	**Metric**	**Slope**	**Intercept**	**R^2**	**MAE**	**RMSE**	**P-Value**	**F-Statistic**
2-Wheeler	XYZ Max	0.074	24.717	0.899	0.504	0.642	2.222e-09	142.478
2-Wheeler	XYZ RMS	0.021	4.980	0.893	0.152	0.192	3.622e-09	133.148
2-Wheeler	XYZ Avg. Power	0.230	79.016	0.818	2.104	2.819	2.547e-07	72.065
Truck(Ta)	XYZ Max	0.101	41.430	0.279	2.385	2.751	4.300e-02	5.029
Truck(Ta)	XYZ RMS	-0.003	11.695	0.003	0.801	0.951	8.393e-01	0.043
Truck(Ta)	XYZ Avg. Power	0.048	171.386	0.004	11.143	13.101	8.269e-01	0.050
Truck(S)	XYZ Max	0.247	24.004	0.882	1.549	1.825	6.536e-07	89.405
Truck(S)	XYZ RMS	0.007	8.383	0.111	0.319	0.380	2.443e-01	1.499
Truck(S)	XYZ Avg. Power	0.000	131.866	0.000	5.219	6.236	9.973e-01	0.000
LCV	XYZ Max	0.166	21.685	0.948	0.593	0.841	9.731e-10	238.106
LCV	XYZ RMS	0.030	5.200	0.925	0.157	0.184	1.071e-08	160.898
LCV	XYZ Avg. Power	0.449	78.216	0.923	2.043	2.809	1.316e-08	155.506
Car	XYZ Max	-0.034	32.588	0.776	0.476	0.549	1.447e-05	45.030
Car	XYZ RMS	-0.006	6.826	0.846	0.064	0.073	1.214e-06	71.490
Car	XYZ Avg. Power	-0.112	103.615	0.899	0.907	1.131	7.533e-08	116.060
Truck(Ma)	XYZ Max	-0.187	63.954	0.595	2.189	2.669	3.297e-03	14.700
Truck(Ma)	XYZ RMS	-0.140	22.199	0.757	1.092	1.375	2.313e-04	31.233
Truck(Ma)	XYZ Avg. Power	-1.804	314.267	0.771	13.663	17.037	1.714e-04	33.718
Truck(Tr)	XYZ Max	0.556	19.406	0.981	1.365	1.547	1.030e-11	623.571
Truck(Tr)	XYZ RMS	0.132	5.295	0.975	0.364	0.422	5.416e-11	470.207
Truck(Tr)	XYZ Avg. Power	2.112	71.058	0.990	3.614	4.352	2.944e-13	1136.777

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Table 6.4 continued from previous page

Vehicle	Metric	Slope	Intercept	R^2	MAE	RMSE	P-Value	F-Statistic
Bus	XYZ Max	1.254	-19.124	0.985	2.481	3.109	2.612e-12	786.681
Bus	XYZ RMS	0.303	-5.198	0.986	0.582	0.718	1.520e-12	862.003
Bus	XYZ Avg. Power	4.497	-77.422	0.989	8.038	9.734	5.233e-13	1031.849
3-Wheeler	XYZ Max	0.130	23.887	0.849	0.516	0.617	1.143e-03	33.731
3-Wheeler	XYZ RMS	-0.023	7.453	0.896	0.067	0.087	3.697e-04	51.511
3-Wheeler	XYZ Avg. Power	-0.487	117.710	0.901	1.277	1.809	3.117e-04	54.831
Tractor(WT)	XYZ Max	0.870	39.815	0.873	1.828	2.164	6.349e-03	27.436
Tractor(WT)	XYZ RMS	0.361	8.204	0.826	0.908	1.078	1.205e-02	19.019
Tractor(WT)	XYZ Avg. Power	4.393	143.666	0.823	11.215	13.281	1.255e-02	18.576
E-Rickshaw	XYZ Max	-0.847	47.615	0.969	0.715	0.905	2.292e-03	95.060
E-Rickshaw	XYZ RMS	-0.272	12.807	0.970	0.250	0.290	2.271e-03	95.674
E-Rickshaw	XYZ Avg. Power	-4.790	201.576	0.969	4.247	5.176	2.367e-03	92.993

Validation of XYZ-Combined Regression Models The combined XYZ-direction regression models were rigorously evaluated using the coefficient of determination (R^2), Root Mean Square Error (RMSE), p-values and F-statistics. For example, the bus model based on the XYZ Max metric achieved an R^2 of 0.985 and an RMSE of 3.109 mm/s^2, with a p-value < 0.001 and an F-statistic of 786.68. Similarly, the model for tridem-axle trucks (Truck(Tr)) based on the XYZ RMS metric exhibited an R^2 of 0.975 and an RMSE of 0.422 mm/s^2, with a p-value < 0.001 and an F-statistic of 470.21. Furthermore, the light commercial vehicle model using the XYZ Avg. Power metric demonstrated an R^2 of 0.923 and an RMSE of 2.809 mm/s^2. Collectively, these validation metrics confirm that the XYZ-combined regression models are statistically robust and exhibit high predictive accuracy in quantifying overall traffic-induced vibrations.

6.2.2 Passenger Car Vibration Equivalence (PCVE)

The Passenger Car Vibration Equivalence (PCVE) framework standardizes the vibration impacts of various vehicle classes by expressing their vibration metrics relative to passenger cars. This normalization facilitates direct comparisons across different vehicle types and speed intervals. The PCVE metrics for each vibration direction i.e. X (longitudinal), Y (lateral) and Z (vertical) are summarized in Tables 6.5, 6.6 and 6.7, respectively.

X-Direction PCVE Metrics

In the X-direction, Table 6.5 presents the PCVE values across different speed intervals. Tractors with trolley (Tractor(WT)) consistently exhibit higher longitudinal vibrational impacts compared to passenger cars, with a PCVE value of 2.0 at 30 km/h and rising to 2.4 at 40 km/h in the Max X metric. Multi-axle trucks (Truck(Ma)) also demonstrate elevated PCVE values, reaching 1.8 at 30 km/h and gradually decreasing to 1.2 by 80 km/h, indicating strong initial vibrations that taper off at higher speeds. Lighter vehicles such as two-wheelers (2-W) and passenger cars (Car) maintain PCVE values around unity across all speeds, reflecting comparable or slightly elevated longitudinal vibrations relative to the baseline.

The RMS X and Average Power X metrics follow similar trends. Tractor(WT) shows PCVE values as high as 4.2 at 40 km/h in RMS and 4.1 in Average Power, substantially exceeding values observed in lighter vehicles. Truck(Ma) also records high RMS values, peaking at 3.1 at 30 km/h and decreasing consistently with speed. In contrast, two-wheelers and cars exhibit RMS and power values close to 1.0 throughout, reinforcing their classification as low-impact vibrational classes in the longitudinal direction.

Table 6.5 PCVE X-Direction Metrics Across Speeds

Metric	Speed (km/h)	2-W	Truck (Ta)	Truck (S)	LCV	Truck (Ma)	Truck (Tr)	Bus	3-W	Tractor (WT)	Car
Max X	30.0	0.9	1.4	0.9	0.8	1.8	1.1	-	0.8	2.0	1.0
	40.0	0.9	1.4	1.0	0.9	1.7	1.2	0.8	0.9	2.4	1.0
	50.0	0.9	1.4	1.1	0.9	1.6	1.4	1.2	0.9	-	1.0
	60.0	1.0	1.4	1.1	1.0	1.5	1.6	1.6	1.0	-	1.0
	70.0	1.0	1.4	1.2	1.0	1.3	1.7	2.0	-	-	1.0
	80.0	1.0	1.4	1.3	1.1	1.2	1.9	2.5	-	-	1.0
RMS X	30.0	0.8	1.9	1.4	0.9	3.1	1.4	-	1.0	3.3	1.0
	40.0	0.9	1.9	1.3	0.9	2.8	1.6	1.0	1.0	4.2	1.0
	50.0	0.9	1.8	1.3	1.0	2.5	1.9	1.6	0.9	-	1.0
	60.0	1.0	1.8	1.3	1.0	2.1	1.9	2.1	0.9	-	1.0
	70.0	1.0	1.7	1.2	1.1	1.8	1.9	2.1	-	-	1.0
	80.0	1.0	1.7	1.2	1.2	1.4	2.3	3.3	-	-	1.0
Average Power X	30.0	0.8	1.9	1.4	0.9	3.1	1.4	-	1.0	3.3	1.0
	40.0	0.9	1.9	1.3	0.9	2.8	1.7	1.0	1.0	4.1	1.0
	50.0	0.9	1.8	1.3	1.0	2.5	1.9	1.5	0.9	-	1.0
	60.0	1.0	1.8	1.3	1.0	2.1	1.9	2.1	0.9	-	1.0
	70.0	1.0	1.7	1.2	1.1	1.8	1.9	2.1	-	-	1.0
	80.0	1.0	1.7	1.2	1.2	1.4	2.3	3.3	-	-	1.0

Y-Direction PCVE Metrics

In the Y-direction, Table 6.6 presents the PCVE values across different vehicle types and speed intervals. Tractors with trolleys (Tractor(WT)) consistently exhibit the highest lateral vibrational responses. In the Max Y metric, Tractor(WT) records a PCVE of 2.5 at 30 km/h, which peaks at 2.7 at 40 km/h. Multi-axle trucks (Truck(Ma)) also show substantial lateral vibration levels, with Max Y values ranging from 2.3 at 30 km/h to 2.4 at 80 km/h. Buses (Bus) follow closely, with PCVE values increasing from 1.6 at 50 km/h to 2.7 at 80 km/h, reflecting their intensified lateral vibration contribution at higher speeds.

The RMS Y and Average Power Y metrics show consistent trends. Tractor(WT) exhibits high lateral energy, with RMS values peaking at 2.9 at 30 km/h and Average Power reaching a maximum of 3.2 at 40 km/h. Truck(Ma) also maintains high RMS values starting at 3.0 at 30 km/h and gradually decreasing to 1.6 at 80 km/h. Bus presents a strong rise in vibrational energy, with RMS and Average Power values both reaching 3.2 and 2.4, respectively, at 80 km/h.

Conversely, lighter vehicles such as two-wheelers (2-W), three-wheelers (3-W) and passenger cars (Car) maintain PCVE values near or below unity across all metrics, indicating minimal lateral vibration impact. Light Commercial Vehicles (LCV) exhibit moderate vibrational responses, with values ranging between 0.8 and 1.4. These findings reinforce that heavy vehicles are the dominant contributors to lateral traffic-induced vibrations, especially under higher-speed operation.

Table 6.6 PCVE Y-Direction Metrics Across Speeds

Metric	Speed (km/h)	2-W	Truck (Ta)	Truck (S)	LCV	Truck (Ma)	Truck (Tr)	Bus	3-W	Tractor (WT)	Car
Max Y	30.0	0.8	1.6	1.1	0.8	2.3	1.4	-	0.9	2.5	1.0
	40.0	0.9	1.5	1.3	1.0	2.2	1.5	1.0	0.9	2.7	1.0
	50.0	0.9	1.7	1.2	0.9	2.2	1.7	1.6	1.0	-	1.0
	60.0	0.9	1.9	1.6	1.2	2.0	2.0	2.2	1.2	-	1.0
	70.0	1.0	1.7	1.4	1.3	2.2	2.3	2.4	-	-	1.0
	80.0	1.1	1.8	1.5	1.4	2.4	2.6	2.7	-	-	1.0
RMS Y	30.0	0.8	1.9	1.4	0.9	3.0	1.4	-	1.0	2.9	1.0
	40.0	0.9	1.8	1.4	0.9	2.7	1.5	1.1	1.1	2.0	1.0
	50.0	0.9	1.8	1.3	1.0	2.4	1.8	1.4	1.1	-	1.0
	60.0	1.0	1.7	1.3	1.0	2.1	2.0	1.8	1.0	-	1.0
	70.0	1.1	1.6	1.3	1.1	1.9	2.3	3.2	-	-	1.0
	80.0	1.2	1.6	1.2	1.2	1.6	2.4	3.2	-	-	1.0
Average Power Y	30.0	0.8	1.9	1.4	0.9	3.0	1.4	-	1.0	2.9	1.0
	40.0	0.9	1.8	1.4	0.9	2.5	1.6	0.9	1.0	3.2	1.0
	50.0	0.9	1.8	1.3	1.0	2.5	1.8	1.5	1.0	-	1.0
	60.0	1.0	1.7	1.3	1.0	2.6	2.0	1.8	2.1	-	1.0
	70.0	1.1	1.6	1.3	1.2	2.3	2.2	2.1	-	-	1.0
	80.0	1.2	1.6	1.2	1.2	2.6	2.4	2.4	-	-	1.0

Z-Direction PCVE Metrics

In the Z-direction, Table 6.7 presents the PCVE values across different vehicle types and speed intervals. Buses (Bus) and tridem-axle trucks (Truck(Tr)) are the most prominent contributors to vertical vibrations. In the Max Z metric, Bus reaches a PCVE of 2.7 and Truck(Tr) reaches 2.6 at 80 km/h. Multi-axle trucks (Truck(Ma)) also show substantial vertical responses, with Max Z values rising from 1.4 at 30 km/h to 2.4 at 80 km/h. Tractors with trolleys (Tractor(WT)) exhibit moderate-to-high vertical impact, peaking at a Max Z value of 2.0 at 40 km/h.

The RMS Z and Average Power Z metrics reflect similar trends. Bus reaches RMS and Average Power values of 2.3 and 2.4, respectively, at 80 km/h, while Truck(Tr) also climbs to 2.3 in both metrics at high speeds. Truck(Ma) shows RMS values increasing from 1.5 at 30 km/h to 2.4 at 80 km/h, with Average Power peaking at 2.6. Tractor(WT) demonstrates stable vertical energy with RMS and Average Power values reaching up to 2.1 at mid-range speeds (40–60 km/h).

In contrast, two-wheelers (2-W), passenger cars (Car) and three-wheelers (3-W) maintain PCVE values around or slightly above unity across all Z-direction metrics, indicating minimal vertical vibrational influence. Light Commercial Vehicles (LCV) exhibit moderate vibration levels, with values ranging from 0.9 to 1.4. Single-axle trucks (Truck(S)) show a gradual rise in PCVE, peaking at 1.9 in the Max Z metric at 80 km/h, indicating a moderate vibrational impact at higher speeds.

Table 6.7 PCVE Z-Direction Metrics Across Speeds

Metric	**Speed (km/h)**	**2-W**	**Truck (Ta)**	**Truck (S)**	**LCV**	**Truck (Ma)**	**Truck (Tr)**	**Bus**	**3-W**	**Tractor (WT)**	**Car**
Max Z	30.0	0.9	1.3	1.1	0.9	1.4	1.2	-	1.0	1.8	1.0
	40.0	0.9	1.5	1.3	1.0	1.6	1.4	1.5	1.1	2.0	1.0
	50.0	0.9	1.7	1.4	1.1	1.8	1.7	1.8	1.1	-	1.0
	60.0	0.9	1.9	1.6	1.2	2.0	2.0	2.1	1.2	-	1.0
	70.0	0.9	2.1	1.8	1.3	2.2	2.3	2.4	-	-	1.0
	80.0	0.9	2.3	1.9	1.4	2.4	2.6	2.7	-	-	1.0
RMS Z	30.0	0.8	1.9	1.4	0.9	1.5	1.3	-	1.1	1.9	1.0
	40.0	0.9	1.4	1.2	1.1	1.6	1.5	1.3	1.1	2.0	1.0
	50.0	0.9	1.8	1.3	1.2	1.8	1.7	1.5	1.1	-	1.0
	60.0	1.0	1.8	1.3	1.2	2.0	1.9	1.8	1.0	-	1.0
	70.0	1.0	2.0	1.7	1.2	2.2	2.1	2.1	-	-	1.0
	80.0	1.0	2.2	1.8	1.3	2.4	2.3	2.3	-	-	1.0
Average Power Z	30.0	0.8	1.9	1.4	0.9	1.4	1.2	-	1.1	1.9	1.0
	40.0	0.9	1.4	1.3	1.1	1.7	1.4	1.3	2.1	2.1	1.0
	50.0	0.9	1.8	1.3	1.2	1.9	1.7	1.6	2.0	-	1.0
	60.0	1.0	1.9	1.5	1.2	2.1	1.7	1.8	2.1	-	1.0
	70.0	0.9	2.1	1.7	1.2	2.3	2.2	2.1	-	-	1.0
	80.0	0.9	2.3	1.8	1.3	2.6	2.4	2.4	-	-	1.0

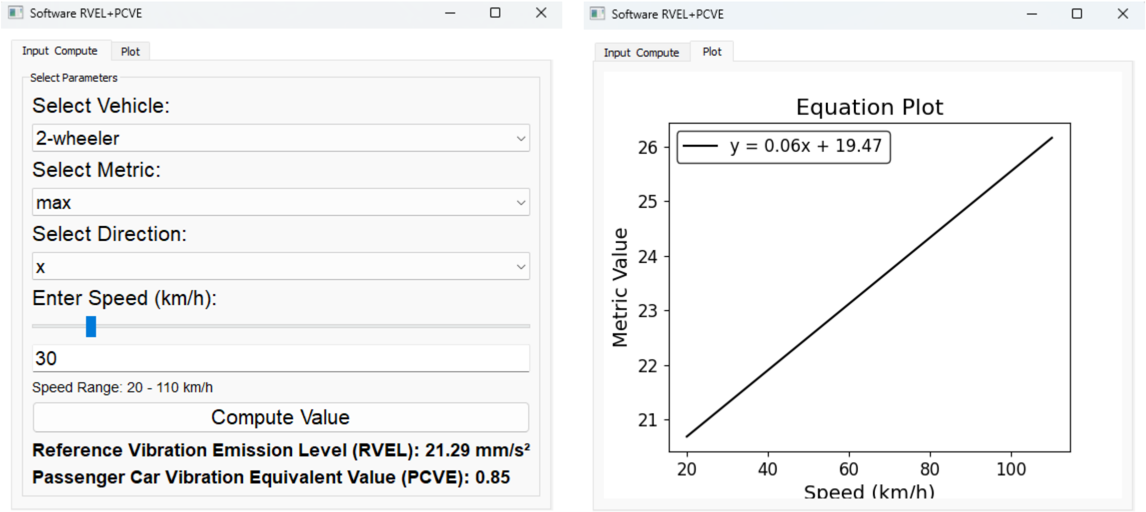
The PCVE analysis across all three vibration directions consistently highlights that heavier vehicle classes, particularly buses and multi-axle trucks are major contributors to traffic-induced vibrations compared to passenger cars. The PCVE values generally increase with vehicle speed, indicating that higher velocities exacerbate vibrational impacts. This standardized measure underscores the necessity for targeted mitigation strategies focusing on heavy vehicle classes to effectively manage and reduce overall traffic-induced vibrations.

6.2.3 Software Implementation

The developed software, RVEL+PCVE, offers an intuitive interface for calculating and visualizing Traffic-Induced Vibrations (TIV) using the RVEL–PCVE frameworks. The software provides dropdown menus and sliders for selecting parameters such as vehicle type (e.g., 2-wheeler), vibrational metric (e.g., maximum amplitude), vibration direction (X, Y, Z) and speed. Users can input speed values within a specified range and calculate the results by clicking the "Compute Value" button.

The interface displays the computed Reference Vibration Emission Level (RVEL) and Passenger Car Vibration Equivalent (PCVE) values in real time, as shown in Figure 6.5a. Additionally, the software dynamically generates plots, such as the linear regression curve between speed and the selected vibrational metric, as illustrated in Figure 6.5b. These features make the software a powerful tool for analyzing and managing TIV in urban environments, providing both numerical results and visual insights.

The software can be downloaded from the following link: **Click here**.



Select Vehicle: 2-wheeler

Select Metric: max

Select Direction: x

Enter Speed (km/h): 30

Speed Range: 20 - 110 km/h

Reference Vibration Emission Level (RVEL): 21.29 mm/s^2

Passenger Car Vibration Equivalent Value (PCVE): 0.85

(a) Graphical User Interface (GUI) of the software.

(b) Linear regression plot of speed versus vibration metric.

Fig. 6.5 Interactive software for RVEL and PCVE calculation and visualization.

6.3 Discussion

This research advances the understanding of Traffic-Induced Vibrations (TIV) by proposing and rigorously evaluating two complementary frameworks: Reference Vibration Emission Levels (RVEL) and Passenger Car Vibration Equivalence (PCVE). The dual approach offers both absolute (*RVEL*) and relative (*PCVE*) measures for capturing the disparate vibration profiles among varied vehicle classes, road surfaces and speed regimes. Leveraging the rich dataset (Tables 6.1–6.4, 6.5–6.7) and the representative plots (Figures 6.1–6.4), the following discussion synthesizes the critical findings and articulates their scientific, engineering and policy implications. Importantly, this section also explains the occurrence of negative slopes in specific vehicles, along with certain weak correlations in the X and Y directions versus stronger trends in the Z axis.

6.3.1 Significance of the RVEL–PCVE Paradigm

6.3.1.1 Why Two Frameworks?

Traditional TIV assessments often rely on generalized thresholds or peak values, which fail to account for the diverse vibrational footprints produced by different vehicle types. The RVEL framework addresses this gap by providing absolute, vehicle-specific vibration baselines. However, absolute metrics alone do not enable intuitive cross-category comparisons. To address this, the PCVE framework normalizes vibrational output relative to a standard passenger car, analogous to Passenger Car Units (PCUs) in traffic modeling. This scaling facilitates transparent assessment of heavier vehicles, which may impose 2-4 times the vibrational impact of a passenger car under similar conditions.

6.3.1.2 Technical Underpinnings

Both RVEL and PCVE are grounded in statistically validated regression models that quantify the effect of vehicle speed on vibration metrics across longitudinal (X), lateral (Y) and vertical (Z) directions. The frameworks incorporate multi-axis data, ensuring that vibration responses unique to each spatial plane are captured. Preprocessing steps such as band-pass filtering and feature extraction (e.g., RMS, peak amplitude, average power) enhance signal fidelity, isolating vehicle-induced dynamics from environmental noise. These calibrated features form the basis of RVEL quantification and PCVE translation, enabling standardized interpretation of traffic-induced vibrations.

6.3.2 Detailed Insights from RVEL Analyses

6.3.2.1 Longitudinal Vibrations (X-Direction)

The strong positive correlations noted for buses and tridem-axle trucks (e.g., slopes near 0.90-0.95 $\mathrm{mm/s^2/km/h}$ and $R^2 > 0.95$) underscore the pronounced role of increasing speed in intensifying longitudinal vibrations. The physical mechanisms include elevated dynamic axle loads at higher velocities and potential resonance with unsprung mass (e.g., tires, axles). This phenomenon is particularly salient for heavier vehicles, whose chassis can transmit larger inertial forces into the pavement.

However, there are negative slopes for certain classes, for instance, Truck(Ta) with $-0.043\,\mathrm{mm/s^2/km/h}$ and E-Rickshaws with $-0.538\,\mathrm{mm/s^2/km/h}$. Some potential explanations include:

- *Stabilizing Mechanisms at Higher Speeds:* E-Rickshaws and smaller trucks often feature lightweight chassis and specialized suspension geometries that enhance stability at higher velocities. As speed increases, these design features reduce longitudinal oscillations, such as pitching and jostling in the longitudinal axis, thereby lowering X-axis vibrations.

- *Partial or Unbalanced Loads:* Vehicles like Truck(Ta) may operate with uneven load distributions. At moderate speeds, mismatches between axle spacing and load can amplify vibrations. However, at higher speeds, the suspension system may stabilize the vehicle, damping these oscillations and resulting in negative correlations.

- *Driver Behavior and Lane Drift:* At higher speeds, drivers tend to adopt smoother steering techniques and maintain consistent lane positioning. This behavioral adaptation reduces the frequency and amplitude of longitudinal vibrations, contributing to the negative slopes observed.

- *Tire Dynamics and Suspension Response:* Stiffer tires, common in E-Rickshaws and smaller trucks, effectively control vertical vibrations but transmit more horizontal forces, increasing variability in the X-axis. Additionally, suspension systems may prioritize vertical damping over longitudinal, making the X-axis more susceptible to speed-related damping.

- *Resonance Avoidance and Damping Ratios:* Vehicles possess inherent resonance frequencies. If operational speeds approach the natural frequency in the Z-axis, vertical vibrations strongly correlate with speed. Conversely, effective damping in the X-axis prevents resonant amplification, resulting in weaker or negative speed–vibration correlations.
- *Aerodynamic Stabilization:* At higher speeds, aerodynamic forces can stabilize the vehicle's longitudinal dynamics. Increased wind resistance reduces the amplitude of longitudinal oscillations, thereby lowering X-axis vibrations as speed increases.
- *Structural Rigidity and Frame Design:* Stiffer chassis constructions transmit vertical vibrations more effectively while isolating horizontal movements. In contrast, flexible structures absorb more longitudinal energy, reducing the apparent correlation between speed and X-axis vibrations.
- *Mass Distribution and Center of Gravity (CoG):* Vehicles with a higher or asymmetrically distributed CoG, such as E-Rickshaws, experience different vibration dynamics. A higher CoG can stabilize vertical load distribution, mitigating longitudinal vibrations as speed increases.

Moreover, the low R^2 (0.082 for Truck(Ta)) signifies that speed alone does not account for much variance in the X-direction for that vehicle class. External variables (load condition, tire pressure, route geometry) likely overshadow speed's role.

6.3.2.2 Lateral Vibrations (Y-Direction)

Lateral vibrations also exhibit strong dependence on speed for heavier vehicles, with slopes often $> 0.70\,\text{mm/s}^2/\text{km/h}$ and high R^2 values, reflecting the influence of track width, center of gravity and side-to-side oscillations under dynamic loading. Nonetheless, some vehicles, for example, Truck(Ta) with a very low R^2 value of 0.050, display minimal correlation, implying that speed alone may not drive lateral motions in such trucks. Load imbalance, uneven tire inflation, or frequent driver steering inputs could overshadow the simple speed–vibration linear relationship.

A conspicuous negative slope is found in E-Rickshaws at $-0.725\,\text{mm/s}^2/\text{km/h}$ with an R^2 value of 0.942, suggesting that as they move faster, the lateral vibrations *drop significantly*. This likely stems from their minimal mass and the presence of stabilizing design features, such as low-lateral compliance suspensions. At moderate speeds, the E-Rickshaw might exhibit lateral "wobble," but at higher velocities, aerodynamic stabilization or a "holding the line" effect reduces net lateral swaying.

Additional explanations for negative slopes in the Y-direction include:

- *Suspension Tuning for Lateral Stability:* Vehicles like E-Rickshaws may have suspensions specifically tuned to enhance lateral stability at higher speeds, reducing side-to-side oscillations.
- *Aerodynamic Wing Effects:* At higher speeds, aerodynamic components can provide additional lateral stability, counteracting side forces and minimizing Y-axis vibrations.
- *Dynamic Load Balancing:* Improved load balancing mechanisms at higher speeds can distribute forces more evenly across the vehicle, reducing lateral vibrations.

6.3.2.3 Vertical Vibrations (Z-Direction) and Combined Metrics (XYZ)

Empirical results consistently classify buses and heavy trucks as dominant vertical vibration sources, with slopes often exceeding $0.35\,\text{mm/s}^2/\text{km/h}$ and $R^2 > 0.90$. These values confirm that vertical dynamics, fueled by high axle loads and stiffer suspensions, can accentuate pavement deflection and dynamic load transfer. Summarizing X, Y and Z into an XYZ metric clarifies each vehicle's total vibrational footprint, consistently showing multi-axle trucks surpassing smaller vehicles across all axes.

E-Rickshaws again exhibit a negative slope (e.g., $-0.167\,\text{mm/s}^2/\text{km/h}$ in Z or -0.847 $\text{mm/s}^2/\text{km/h}$ in XYZ), implying a sharp reduction in overall vibrations at higher speeds. The plausible reasons match those discussed earlier, including stabilizing geometry, lighter mass and minimal unsprung mass. Some short-wheelbase vehicles can also “smooth out” vibrations if their natural bounce frequency is less excited at higher speeds.

Further explanations for negative slopes in the Z-direction include:

- *Enhanced Vertical Damping:* Vehicles like E-Rickshaws may have enhanced vertical damping mechanisms that become more effective at higher speeds, reducing Z-axis vibrations.
- *Aerodynamic Load Compensation:* Aerodynamic forces can counteract vertical loads, stabilizing the vehicle and minimizing vertical oscillations as speed increases.
- *Suspension Locking Mechanisms:* Some vehicles employ suspension locking mechanisms at higher speeds to reduce vertical movement, thereby decreasing Z-axis vibrations.

The validated regression models confirm that vehicle speed is a significant driver of traffic-induced vibrations, especially in the vertical and combined directions. High coefficients of determination for buses and tridem trucks in Z Avg. Power and XYZ Max metrics ($R^2 > 0.98$) indicate strong linear scaling of vibration with speed, driven by rigid axle configurations and limited suspension damping.

Lateral vibrations exhibit greater variability. While buses and multi-axle trucks show positive correlations due to mass and track width, Truck Ta displays a low R^2 near 0.05, suggesting that lateral dynamics in such vehicles are influenced more by loading asymmetry, tire imbalance, or steering variability than by speed.

E-Rickshaws consistently show strong negative slopes and high R^2, particularly in Y and Z directions, indicating reduced vibration at higher speeds. This behavior likely stems from lightweight frames, low center of gravity and aerodynamic stabilization effects that minimize oscillations at elevated velocities.

The XYZ-direction metrics consolidate these effects, with buses and heavy trucks exhibiting high slopes and strong fit, validating the RVEL framework. In contrast, lighter vehicles show weaker speed–vibration coupling, aligning with their comfort-tuned suspensions.

These findings highlight that while speed is a dominant factor, vibration behavior is modulated by structural dynamics, suspension design and loading patterns. The RVEL and PCVE frameworks effectively capture these trends, supporting their application in vibration-aware vehicle assessment and infrastructure design.

6.3.3 Certain Weak Correlations in X/Y vs. Stronger Z Trends

Data collection was conducted in a controlled environment, while many heavier vehicles exhibit strong speed–vibration correlations across all three axes (X: longitudinal, Y: lateral, Z: vertical), certain classes like Truck(Ta) and three-wheelers show robust correlations primarily in the Z-direction with weaker associations in X and Y. This can be attributed to the following factors:

- Suspension Tuning and Vertical Oscillation Control: Suspensions in these vehicles are optimized to mitigate vertical oscillations, resulting in clear speed-dependent vertical vibration patterns. However, longitudinal and lateral damping is less effective, making X and Y vibrations more susceptible to driver inputs and minor road irregularities.

- Driver Inputs and Dynamic Steering Behavior: Horizontal vibrations are significantly influenced by steering actions and vehicle handling. Minor steering corrections or lateral drifts introduce variability in X/Y axes not directly proportional to speed, weakening their correlation.

- Weight Transfer and Vehicle Stability: Acceleration and deceleration cause dynamic weight shifts, altering mass distribution and affecting longitudinal and lateral stability. This disrupts speed–vibration correlations in X and Y axes while vertical load remains governed by axle loads and speed.

- Tire Characteristics and Dynamic Response: Tire stiffness, type and pressure influence vibration transmission. Stiffer tires better control vertical vibrations but transmit more horizontal forces, increasing X/Y variability.

- Mass Distribution and Center of Gravity (CoG): Higher or asymmetrically distributed CoG in some vehicles exacerbates lateral sway while stabilizing vertical vibrations, contributing to stronger Z correlations.

- Aerodynamic Influences at Higher Speeds: At higher speeds, aerodynamic forces stabilize vertical movements, enhancing Z correlations. However, they can introduce unpredictable lateral forces, weakening X/Y correlations.

- Resonance Frequencies and Damping Ratios: Vehicles have inherent resonance frequencies in each axis. If operational speeds approach Z-axis resonances, vertical vibrations strongly correlate with speed, while X/Y vibrations may remain damped, weakening their correlations.

- Structural Rigidity and Frame Design: Stiffer chassis transmit vertical vibrations more effectively while isolating horizontal movements. Flexible structures absorb more horizontal energy, reducing X/Y speed correlations.

In summary, the weaker speed-vibration correlations in X and Y axes for certain vehicle classes are due to the interplay between suspension design, driver behavior, weight dynamics, tire properties, aerodynamic forces, resonance characteristics and structural rigidity. The controlled measurement environment further isolates these effects, highlighting that vertical vibrations are predominantly speed-driven, whereas horizontal vibrations are influenced by variable factors. Hence, negative or weak X/Y correlations do not necessarily contradict fundamental TIV principles but rather highlight that different mechanical or behavioral factors may dominate in certain classes.

6.3.4 PCVE Findings: Relative Comparisons and Practical Utility

6.3.4.1 Passenger-Car-Equivalent Vibration Factors

By dividing a given vehicle class's vibrational metric by that of a passenger car at the same speed, PCVE reveals a dimensionless ratio indicative of how many "car-equivalents" of vibration the heavier vehicle imparts. For instance, a multi-axle truck or a tractor-trolley combination might register a PCVE of 2.0–3.0 in vertical amplitude, signifying that its dynamic forces can be triple those of a passenger car (Tables 6.5–6.7). Such normalized values facilitate:

- Cross-Vehicle Comparisons: A simple numeric scale to assess whether a tandem-axle truck is, say, 1.5 or 2.0 times more impactful than a baseline car.
- Unified Planning Tool: Urban planners, familiar with PCUs for congestion modeling, can adopt PCVE to integrate vibration-related impacts into corridor design or traffic demand forecasting.
- Adaptive Traffic Policies: Authorities may restrict or modulate speeds of vehicles exceeding a critical PCVE (e.g., 2.5) on sensitive routes or near vibration-intolerant infrastructure.

6.3.4.2 Implications for Noise, Comfort and Road Stress

Although the analysis centers on vibrational metrics, a relative measure like PCVE naturally extends to occupant comfort and noise exposure considerations. A higher PCVE often correlates with augmented low-frequency vibration within the vehicle cabin, potentially causing driver fatigue or passenger discomfort. From a pavement-stress perspective, cumulative high PCVE pass-bys accelerate surface degradation, underscore the necessity for more robust materials or damping layers and support periodic maintenance scheduling at intervals proportional to traffic's "vibrational load."

6.3.5 Engineering and Policy Ramifications

6.3.5.1 Roadway Preservation and Pavement Design

The RVEL-PCVE results highlight the disproportionate TIV contributions from multi-axle trucks and large buses, indicating a direct link between heavier axle loads at elevated speeds and accelerated pavement wear. Incorporating RVEL-based regressions and PCVE thresholds into pavement design standards (e.g., for local highways or arterial roads) enables:

1. *Damping-Focused Designs:* Adoption of thicker subgrade, polymer-modified asphalt, or geocell reinforcements in "high PCVE" corridors.
2. *Predictive Maintenance Scheduling:* Prioritizing resurfacings on routes characterized by frequent high-PCVE traffic (e.g., logistic corridors with multi-axle freight).
3. *Speed-Restricted Lanes:* Segregating traffic so that exceptionally heavy vehicles travel at moderated speeds or on specifically fortified lanes, reducing cumulative damage.

6.3.5.2 Protecting Sensitive Structures

Monitoring PCVE levels near historically or functionally sensitive buildings (e.g., heritage sites, hospitals, scientific laboratories) can inform stringent local regulations. For example, if a structure cannot tolerate vibrations above 2.0 times the baseline passenger-car amplitude (in the Z-direction), authorities might impose a 40 km/h cap on trucks with a PCVE exceeding 2.0 in that zone. This scientific grounding ensures that policymaking is neither overly restrictive nor permissive, but aligned with measurable vibration thresholds, thereby mitigating crack formation, occupant discomfort and potential structural fatigue.

6.3.5.3 Vehicle Dynamics and Design Innovations

The finding that certain classes consistently show higher RVEL slopes and elevated PCVE across all three axes underscores a need for next-generation heavy-vehicle designs. Active or semi-active suspensions, refined load distribution and even hybrid/electric drivetrains (less engine vibration) can collectively reduce the vibrational footprint. Tiered regulations rewarding lower PCVE vehicles via tax incentives or expanded route access could motivate manufacturers to deploy advanced damping materials, intelligent suspension calibrations and aerodynamic improvements that minimize TIV.

6.3.6 Overall Explanations for Negative Slopes and Directional Discrepancies

A recurring question pertains to vehicles (e.g., Truck(Ta) and E-Rickshaw) showing negative slopes or low regression (R^2) in X/Y but stronger correlations in Z. Key points are:

- Negative Slopes: Some vehicle classes exhibit a distinct drop in vibrations at higher speeds, presumably due to suspension stabilization, minimized rolling/pitch at mid-to-high speed, or improved driver control in a more stable velocity range. For e-rickshaws, lightweight bodies can reduce oscillations once the vehicle transitions above a certain speed, leading to an inverse relationship between speed and X/Y vibrations.

- Low R^2 in X/Y but High in Z: In lateral or longitudinal directions, random driver inputs (steering correction, lane drift) or partial load balancing cause erratic variations that overshadow the speed effect. Conversely, the vertical axis remains dominated by consistent axle hopping or chassis bounce that strongly scales with speed.
- Unique Suspension/Load Configurations: Trucks carrying uneven loads or special-purpose vehicles (tractor with trolley, e-rickshaw) may shift weight distribution in a manner that reduces certain directional vibrations at higher speeds. The net effect is a negative or negligible slope in X/Y metrics, even if Z remains strongly speed-dependent.

Hence, the observation of “some vehicles not following good regression in X and Y but showing strong correlation in Z” is inherently tied to vehicle geometry, driver behavior, load distribution and speed-induced stability phenomena. Rather than contradicting TIV principles, these anomalies highlight the multi-factor complexity behind directional vibrations in certain classes.

The RVEL-PCVE approach provides a granular yet integrated perspective on traffic-induced vibrations. Negative slopes and weaker correlations in specific directions (X or Y) are not outliers but reflections of vehicle-specific and driver-specific behaviors at varying speeds. By interpreting these patterns within the broader context of multi-axis vibration data, it becomes clear which vehicles pose the greatest vibration risk (heavy trucks, buses) at particular speed ranges and why some classes (e.g., e-rickshaws, partially loaded trucks) invert or dampen TIV at higher speeds. Moreover, the frameworks clarify how best to regulate speeds, design pavements and adopt structural reinforcements to preemptively control TIV’s adverse effects on infrastructure and occupant comfort. This standardized methodology, founded on both absolute reference emission levels and passenger-car-equivalent scaling, represents a critical step toward scientifically informed, targeted interventions for managing the full spectrum of traffic-induced vibrations in contemporary urban environments.

6.4 Conclusion

This study presents a novel dual-framework approach, combining Reference Vibration Emission Levels (RVEL) and Passenger Car Vibration Equivalence (PCVE), to address the complexities of Traffic-Induced Vibrations (TIV) assessment and mitigation. Leveraging a robust dataset of 9,257 single-vehicle pass-by events collected in Gorakhpur, Uttar Pradesh, the proposed methodology introduces a standardized and scalable solution for characterizing and comparing vibrational impacts across diverse vehicle types, ranging from two-wheelers to multi-axle trucks. By employing advanced signal processing techniques and statistical modeling, the frameworks provide a data-driven foundation for real-time vibration analysis and decision-making.

RVEL Contributions The RVEL framework quantifies absolute vibration metrics, including maximum amplitude, Root Mean Square (RMS) and average power, for each vehicle category under varying speeds. By addressing the limitations of generalized threshold-based guidelines, RVEL enables granular assessments that account for dynamic load distributions and low-frequency resonances unique to heavy vehicles. The high coefficients of determination ($R^2 > 0.90$) validate the linear regression models' accuracy in correlating vehicle speed with vibration intensity across longitudinal (X), lateral (Y) and vertical (Z) axes. The findings highlight the disproportionate contributions of multi-axle trucks and buses to urban vibrational environments, underscoring their role in accelerating infrastructure wear and elevating risks for vibration-sensitive zones.

PCVE Framework and Utility Building on RVEL metrics, the PCVE framework introduces a relative vibration scale by translating vibrational impacts into passenger-car-equivalent units, analogous to the Passenger Car Unit (PCU) in traffic engineering. This relative index enables intuitive cross-category comparisons, facilitating the identification of vehicle types with higher vibrational footprints. For example, specific truck classes exhibit up to three times the vibrational impact of standard passenger cars at equivalent speeds. PCVE provides actionable insights for policymakers and urban planners to prioritize interventions, such as speed regulations, lane segregation and targeted infrastructure reinforcements. By offering a standardized and communicable metric, PCVE bridges the gap between technical vibration assessments and practical urban management strategies.

Technological Advancements and Real-Time Integration The dual-framework approach is operationalized through a Python-based software tool, enabling real-time predictions, visualization and adaptive calibration. The integration of these frameworks into intelligent transportation systems (ITS) enhances their applicability for on-site evaluations, automated traffic monitoring and data-driven decision-making. This technological capability supports adaptive traffic management strategies, including predictive maintenance and dynamic traffic control in high-vibration corridors.

Broader Applications and Implications The RVEL and PCVE frameworks extend beyond traffic planning to address broader challenges in urban transportation and environmental management:

- Environmental Sustainability: The frameworks support holistic environmental assessments by integrating vibration analysis with noise and air quality metrics, aiding in the development of sustainable urban transportation systems.

- Infrastructure Resilience: Targeted identification of high-impact vehicles enables the implementation of vibration mitigation measures, such as damping layers, reinforced road designs and site-specific speed limits.

- Urban Planning and Policy: Policymakers can leverage PCVE to develop comprehensive traffic zoning regulations, prioritize maintenance schedules and protect vibration-sensitive zones, including heritage sites and high-precision facilities.

- Intelligent Vehicle Design: Vehicle manufacturers can use RVEL and PCVE insights to optimize suspension systems and reduce vibrational emissions, enhancing passenger comfort and minimizing infrastructure wear.

- Public Health and Urban Livability: Reducing TIV improves urban health outcomes by minimizing vibration-induced discomfort and stress among city dwellers, contributing to overall well-being.

- Economic Benefits: The frameworks facilitate cost-effective transportation management by reducing infrastructure repair costs and mitigating the economic burden of health-related expenses linked to TIV.