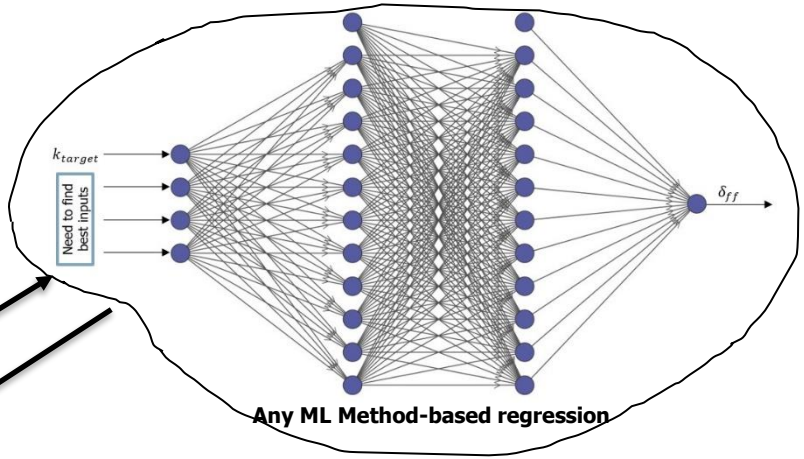
Supervised Learning-based Feed Forward Controller

Sivaraman Sivaraj (DIWID24)

Control Architecture with Replacement



Feed Forward Control
$\delta_{ff} = \arctan(l * k_{target})$

δ_{ff}

Position Controller

k_{target}

$\delta_{ff} + \delta_{adaptive}$

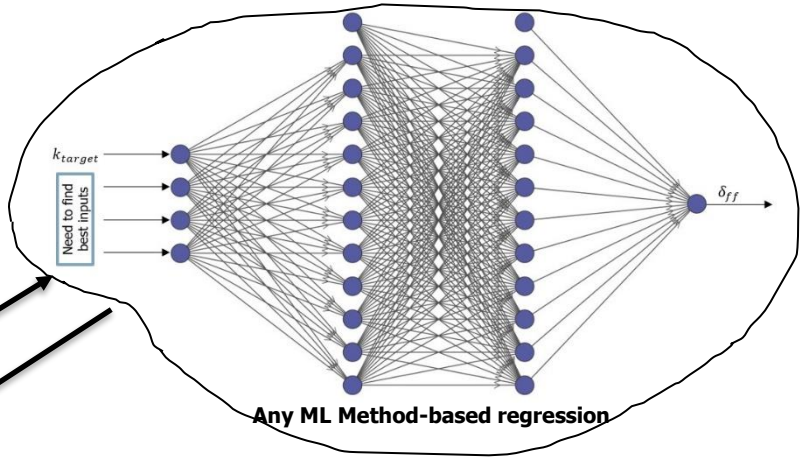
Opel Astra

Present States

V_{actual}, k_{actual}

Adaptive Controller

$\delta_{adaptive}$



Feed Forward Control
$\delta_{ff} = \arctan(l * k_{target})$

δ_{ff}

Position Controller

k_{target}

$\delta_{ff} + \delta_{feedback}$

Plant Dynamics

Present States

V_{actual}, k_{actual}

Feedback Control

$\delta_{feedback}$

Development Strategy:

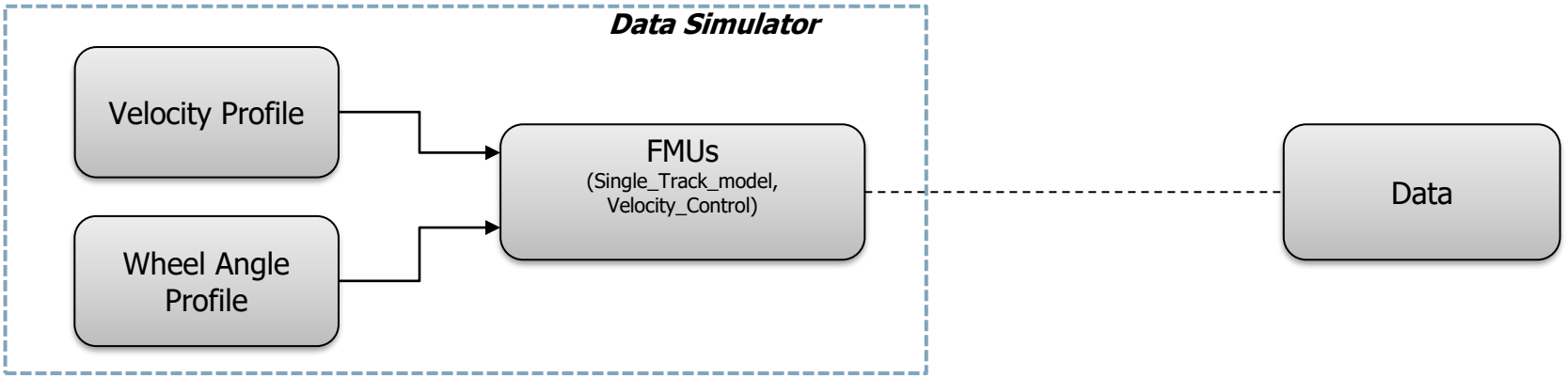
In Training:

In Deployment:

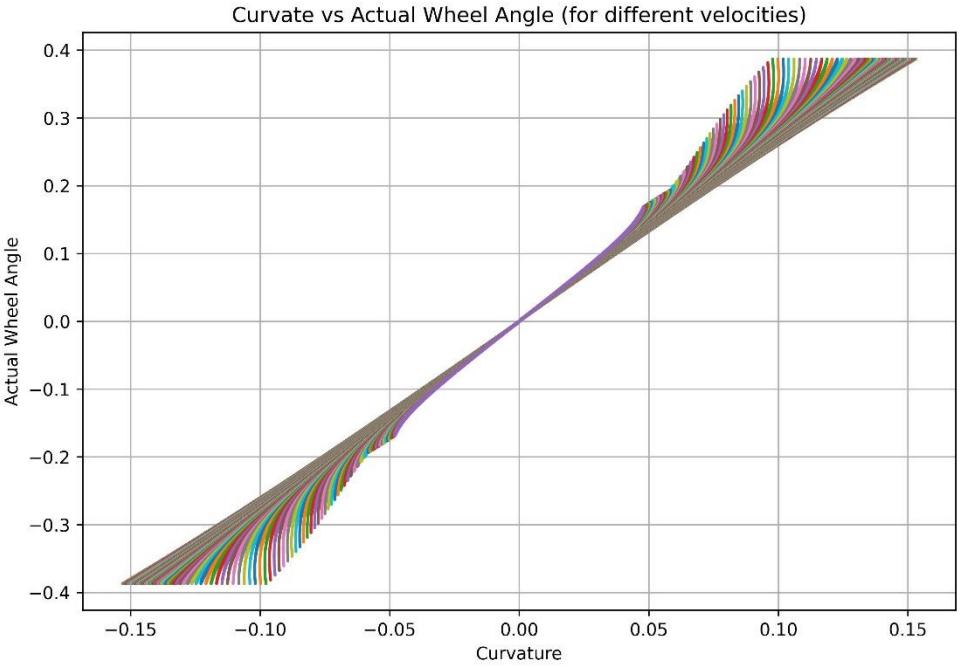
Data Generation – Using FMU :

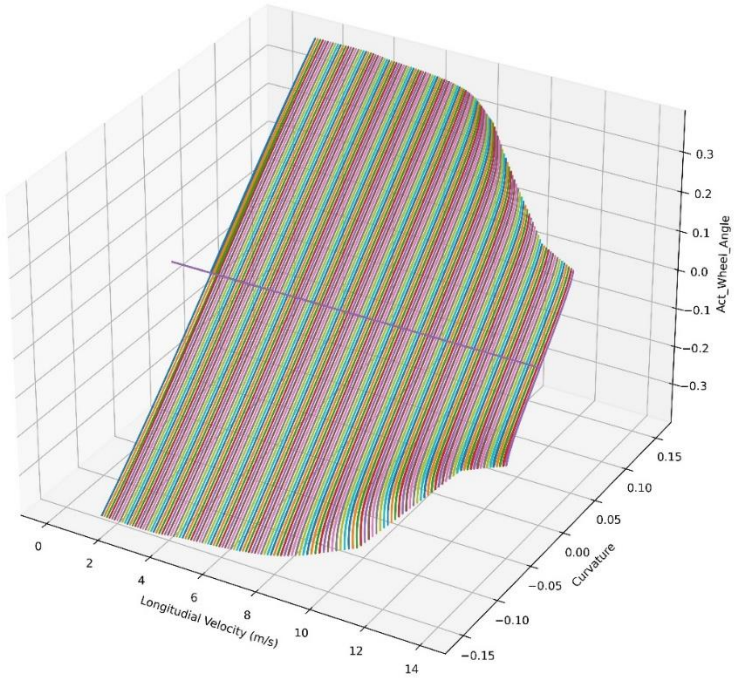
- Brut Force Method
  - Keeping the constant Velocity & Varying Wheel Angle
  - Keeping the Wheel Angle Constant & Varying Velocity

- Random Profile



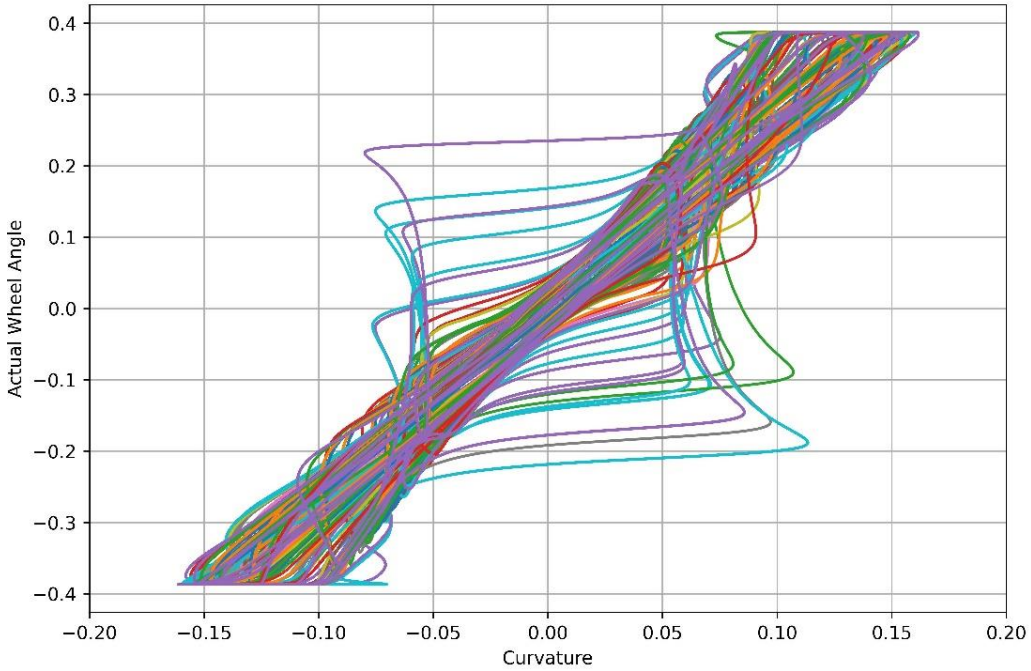
Brut Force Data : (constant velocity & varying wheel Angle)

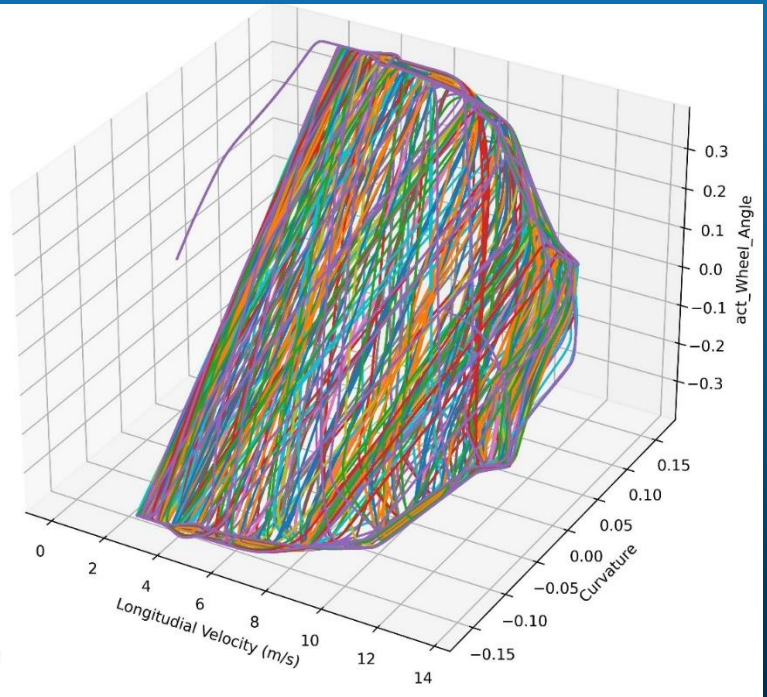




v_p_200ms	v_p_100ms	vel_x	curv_prev_100ms	curv	curv_fut_100ms	curv_fut_200ms	act_wheel_rad
-1.9e-05	-1.8e-05	-1.8e-05	0.99	0.99	0.99	0.99	1

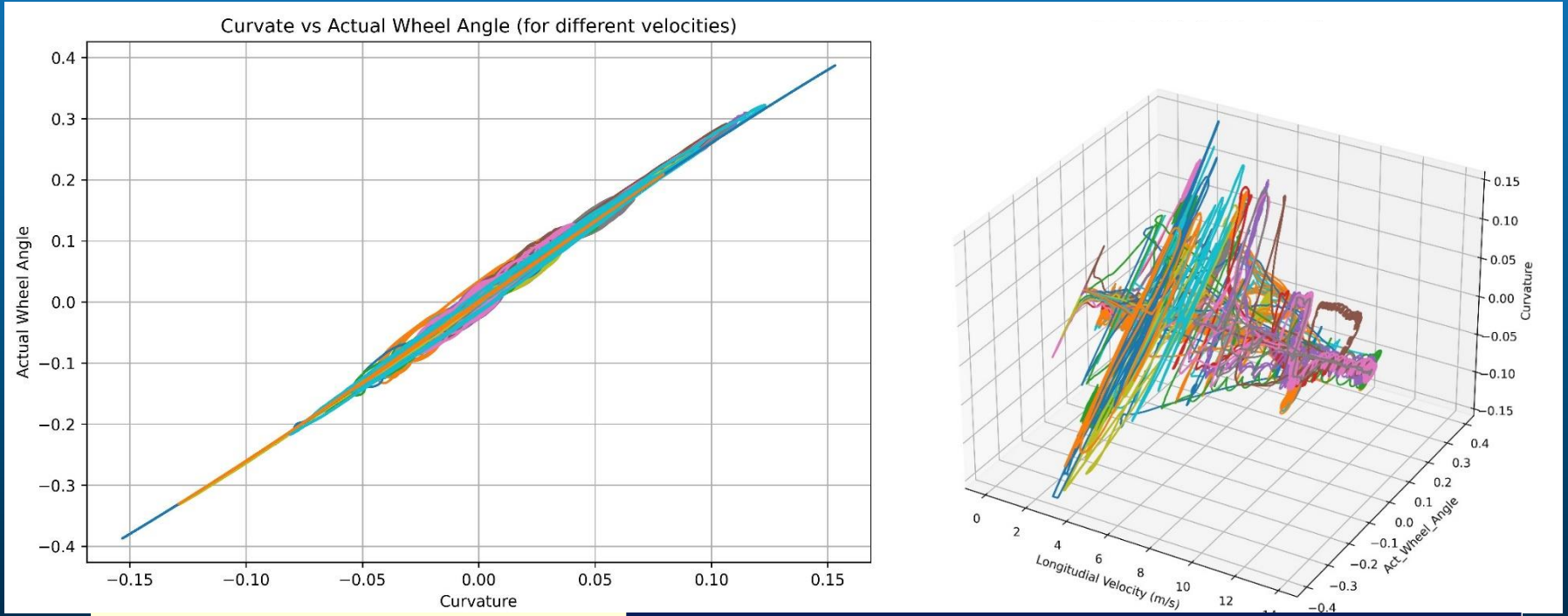
Sine Wave Signal's Data Generation : (Velocity & Wheel Angle)





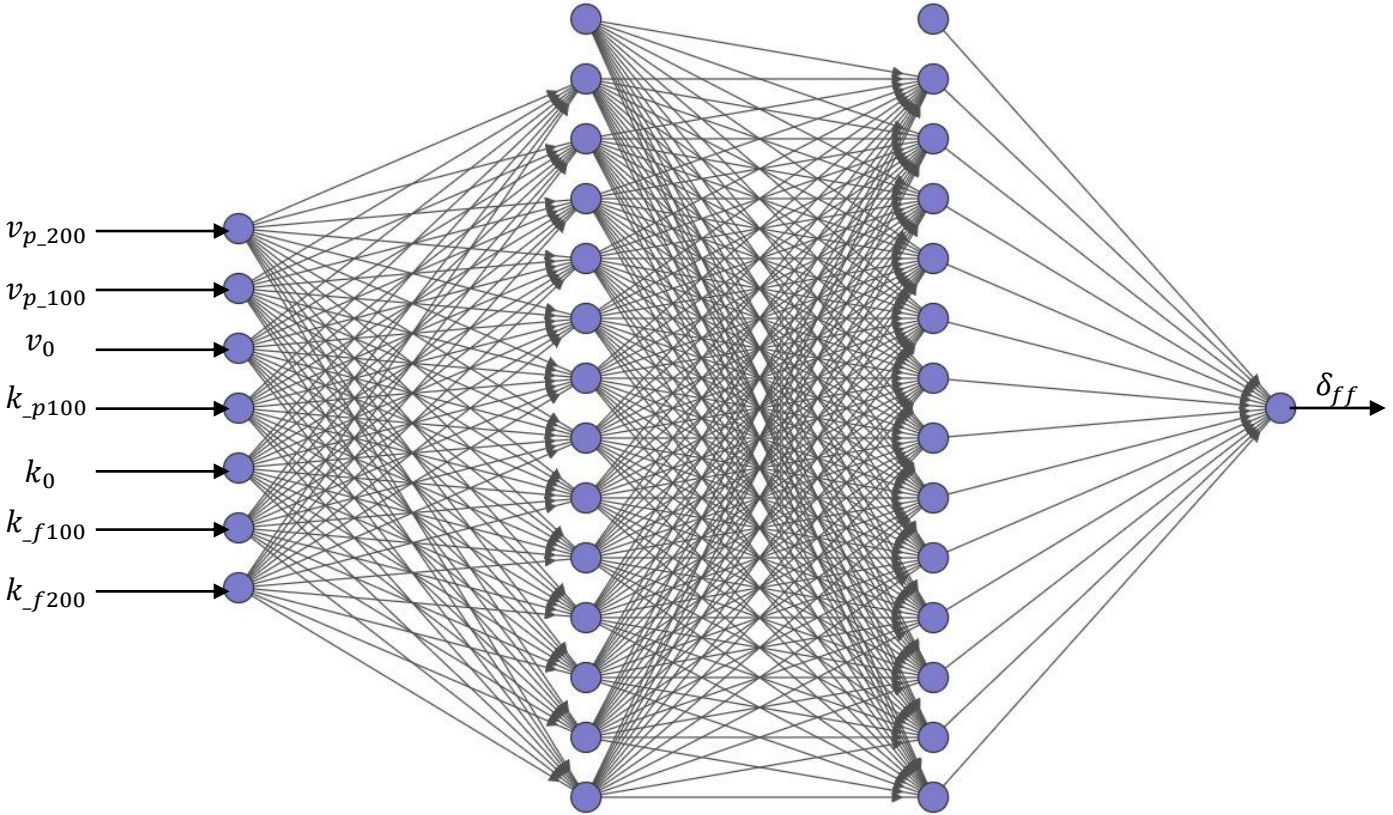
v_p_200ms	v_p_100ms	vel_x	curv_prev_100ms	curv	curv_fut_100ms	curv_fut_200ms	act_wheel_rad
0.091	0.09	0.088	0.98	0.99	0.99	0.99	1

Scenario Data:

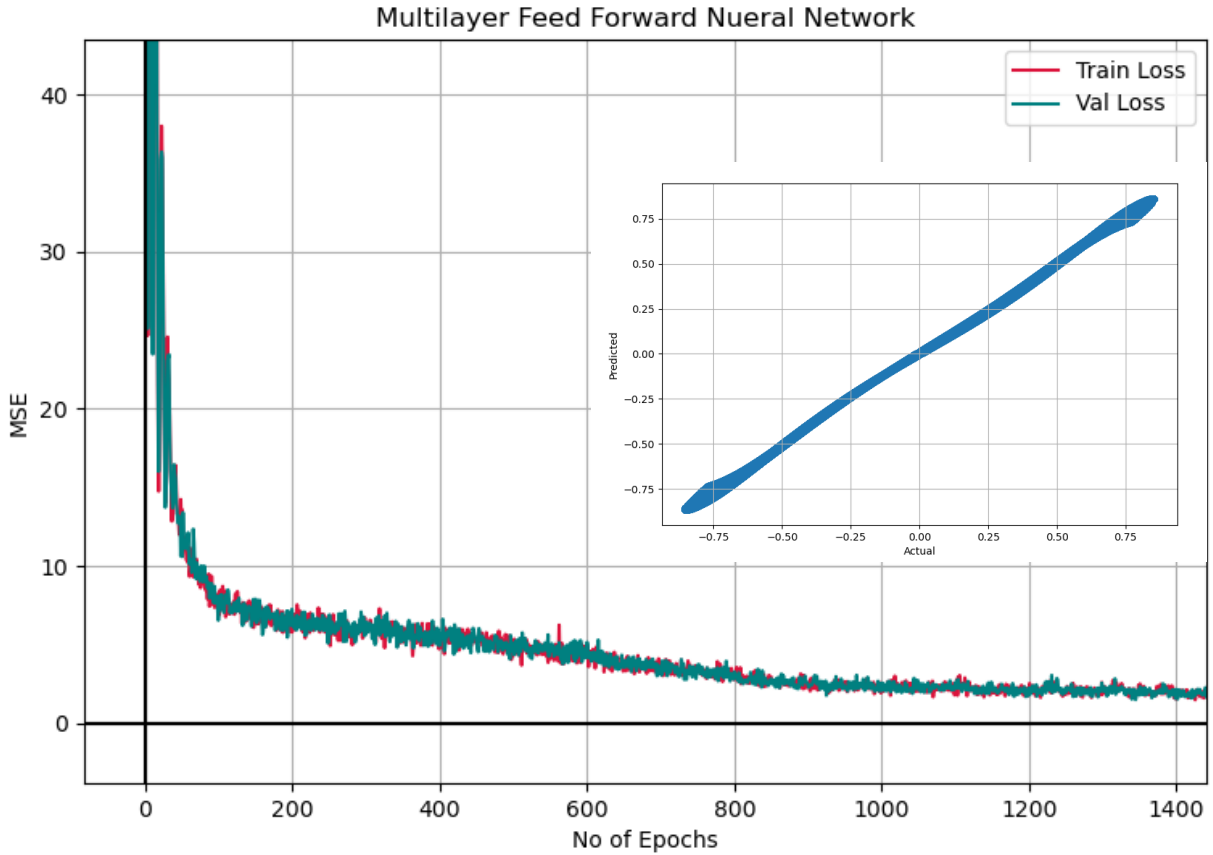


v_p_200ms	v_p_100ms	vel_x	curv_prev_100ms	curv	curv_fut_100ms	curv_fut_200ms	act_wheel_rad
-0.036	-0.036	-0.036	1	1	1	1	1

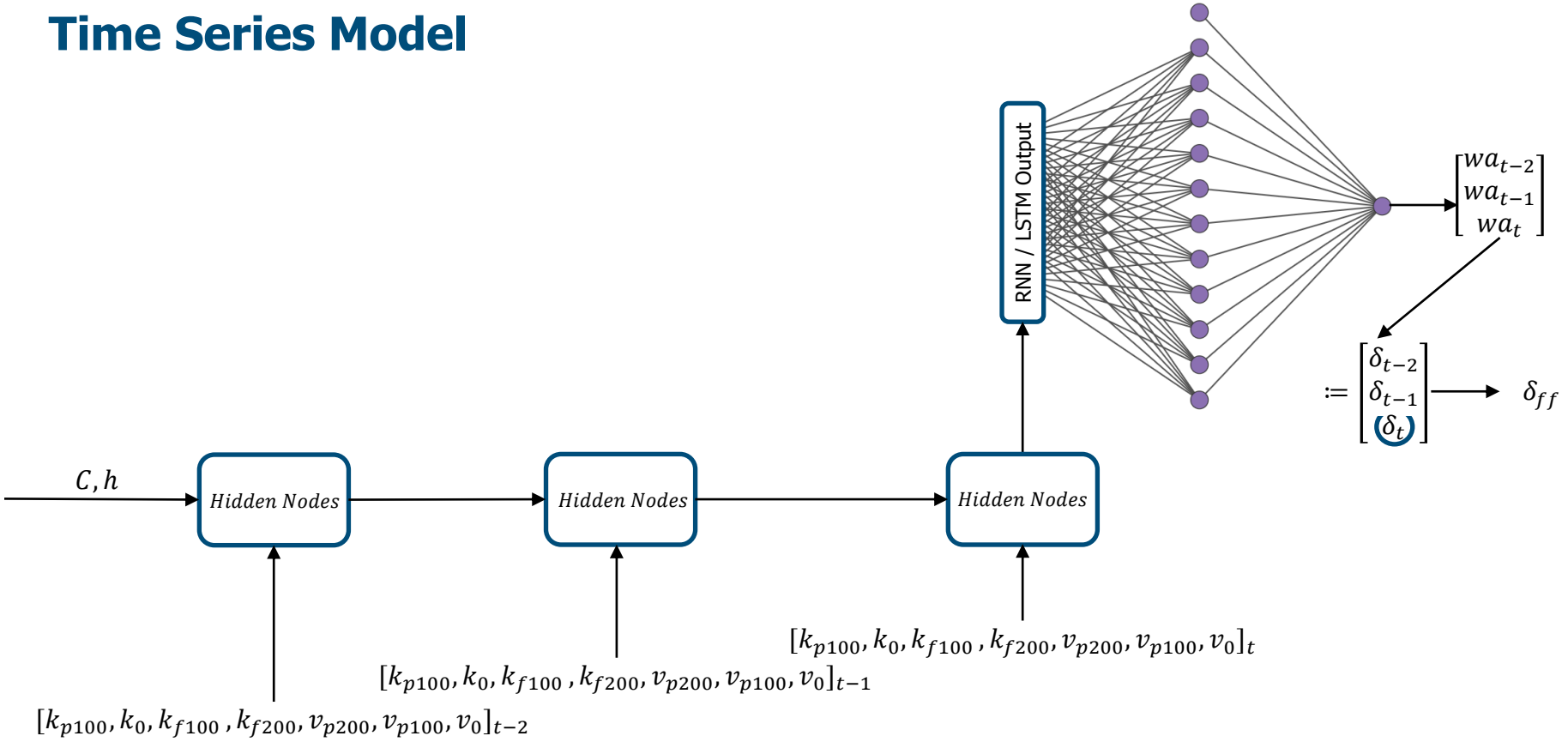
New Model (with past velocity memory)



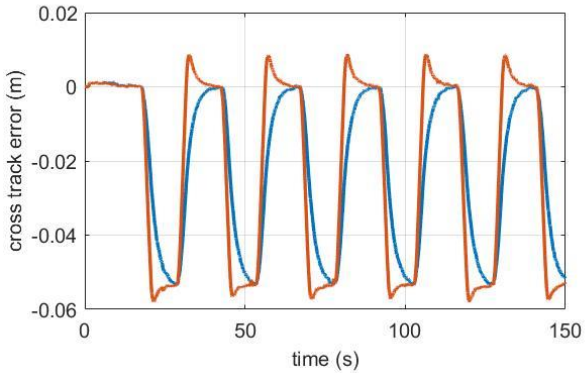
On Train – Validation Perspective:

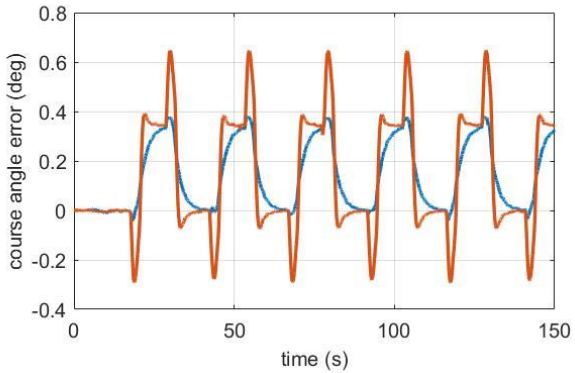


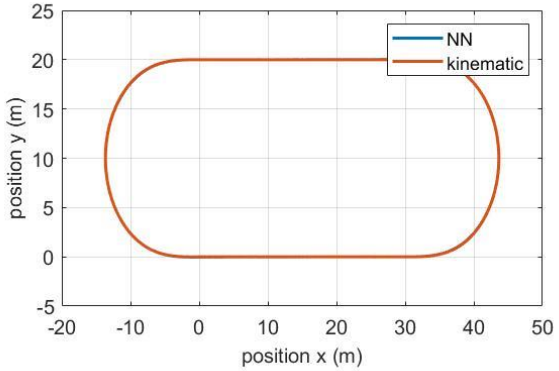
Time Series Model

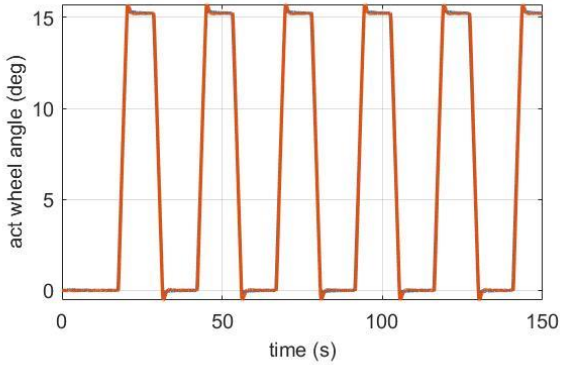


Result : Scenario 01

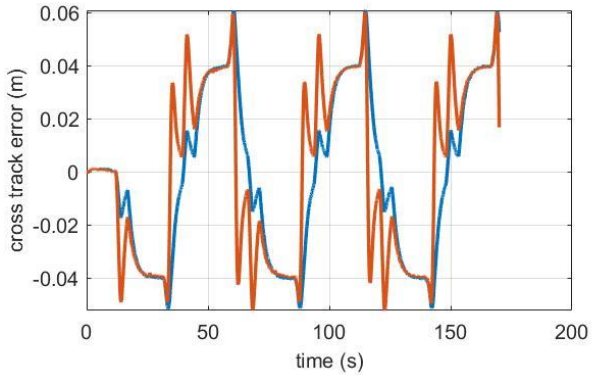


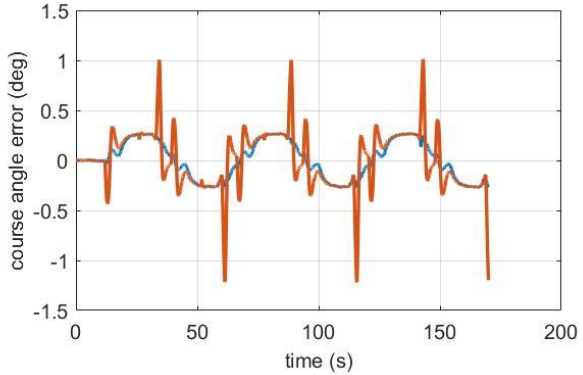


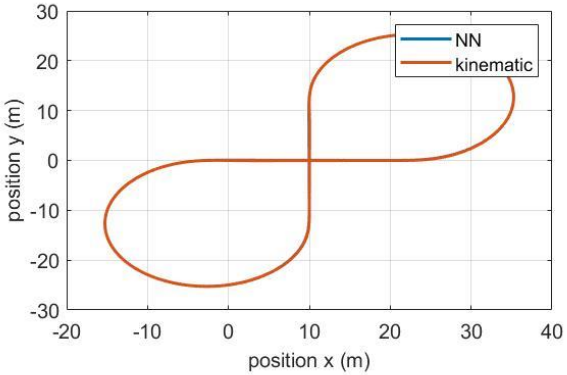


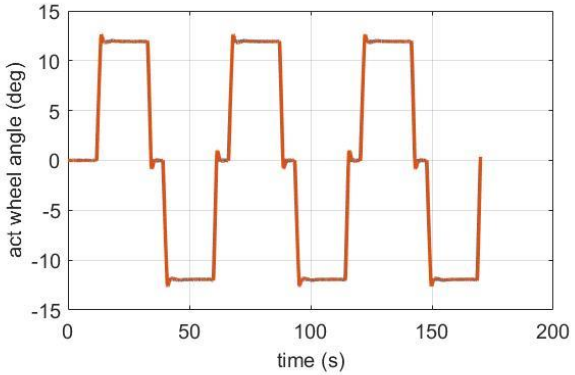


Result : Scenario 02

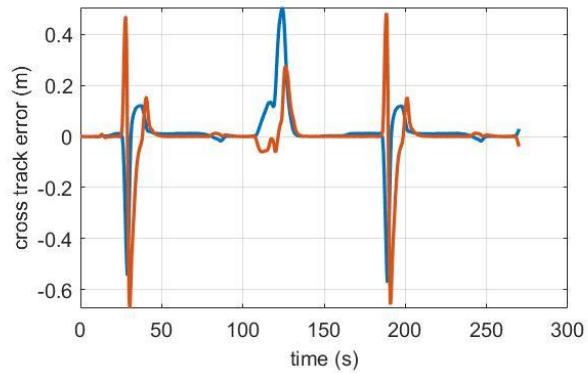


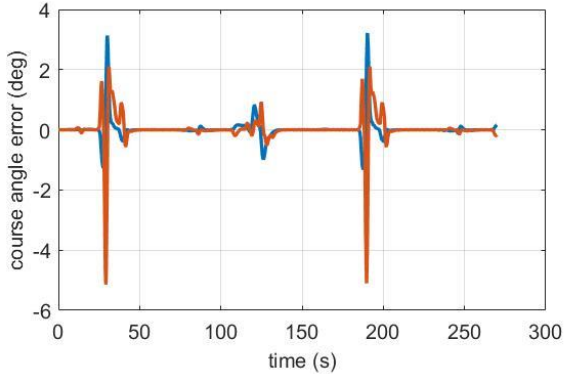


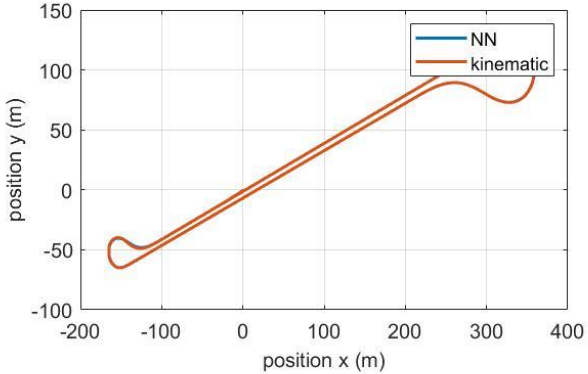


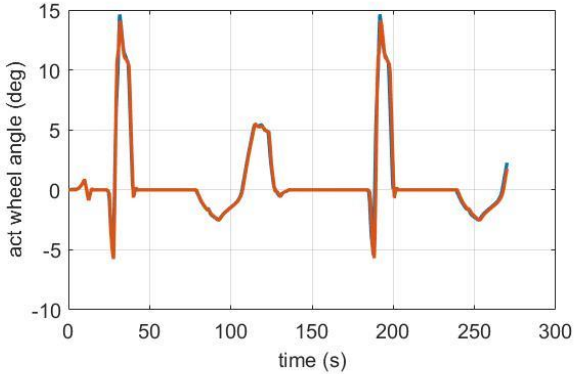


Result : Scenario 03

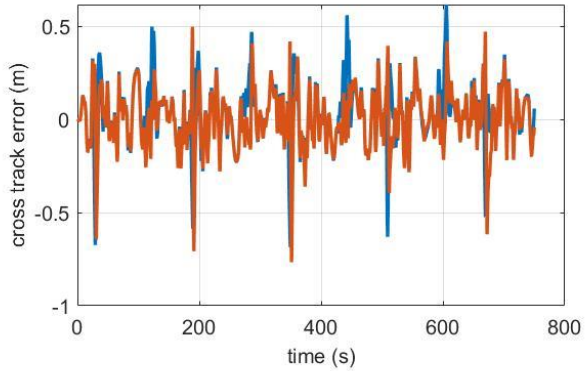


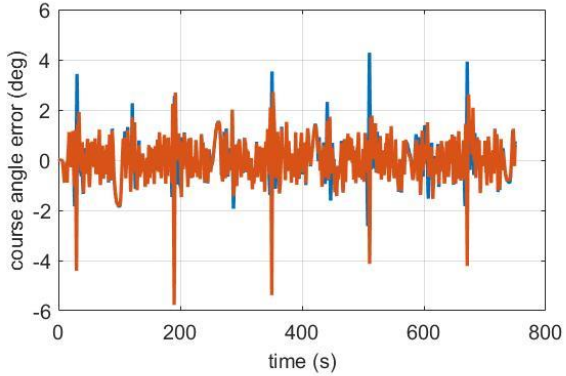


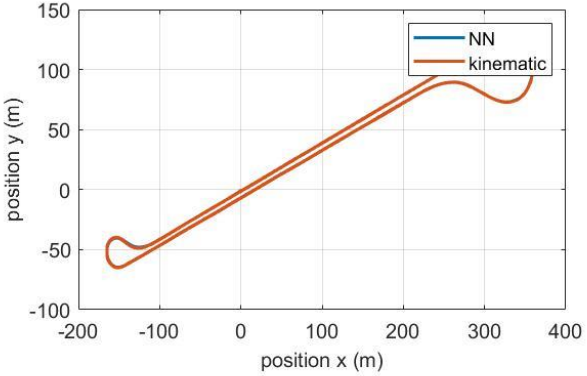


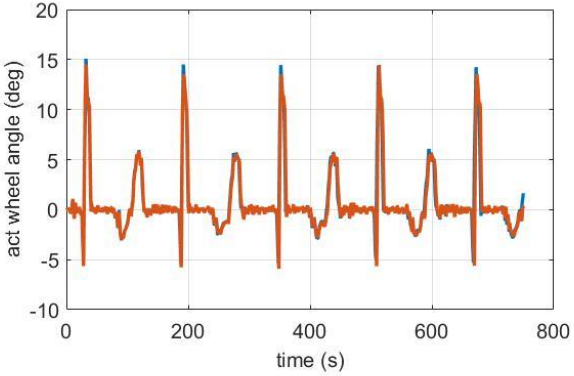


Result : Scenario 10









Investigation on State Space Range

$Velocity \quad \rightarrow \left\{1.5\ to\ 14 \frac{m}{s}\right\}$

$Wheel\ Angle \rightarrow \{-22.9^\circ\ to\ 22.9^\circ\}$

$Curvature\ Rate \rightarrow \{-0.15\ to\ 0.15\}\ \ (Data\ need\ to\ be\ generated)\ caution: lat_{accelration} is\ UB = 8\ m/s^2$

Understanding the Data: (Correlation Between States)

- Covariance Correlation Coefficient:

$$Cov\ (X,Y) = \frac{\sum(X\ - mean(X)) * (Y\ - mean(Y))}{n-1}$$

- Pearson's Correlation Coefficient:

$$Pearson(X,Y) = \frac{Cov\ (X,Y)}{StdDev(X) * StdDev(Y)}$$

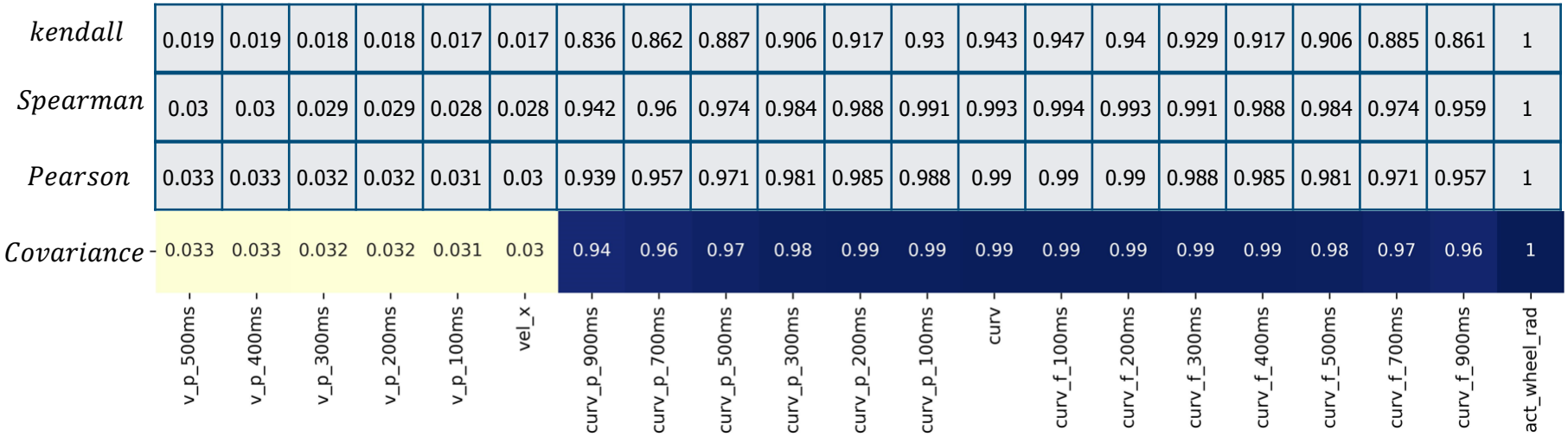
- Spearman's Correlation Coefficient:

$$Spearman\ (X,Y) = \frac{Covariance(rank(X), rank(Y))}{(stdDev\big(rank(X)\big) * stdDev(rank(Y)))}$$

- Kendall's Correlation Coefficient:

$$\tau = \frac{2}{n(n-1)} \sum_{i<j} \text{sgn}\big(x_i\ - x_j\big)\ \text{sgn}(y_i\ - y_j)$$

Correlations – Collective Data:



	v_p_500ms	v_p_400ms	v_p_300ms	v_p_200ms	v_p_100ms	vel_x	curv_p_900ms	curv_p_700ms	curv_p_500ms	curv_p_300ms	curv_p_200ms	curv_p_100ms	curv	curv_f_100ms	curv_f_200ms	curv_f_300ms	curv_f_400ms	curv_f_500ms	curv_f_700ms	curv_f_900ms	act_wheel_rad
kendall	0.019	0.019	0.018	0.018	0.017	0.017	0.836	0.862	0.887	0.906	0.917	0.93	0.943	0.947	0.94	0.929	0.917	0.906	0.885	0.861	1
Spearman	0.03	0.03	0.029	0.029	0.028	0.028	0.942	0.96	0.974	0.984	0.988	0.991	0.993	0.994	0.993	0.991	0.988	0.984	0.974	0.959	1
Pearson	0.033	0.033	0.032	0.032	0.031	0.03	0.939	0.957	0.971	0.981	0.985	0.988	0.99	0.99	0.99	0.988	0.985	0.981	0.971	0.957	1
Covariance	0.033	0.033	0.032	0.032	0.031	0.03	0.94	0.96	0.97	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.97	0.96	1

Correlations - Constant Velocity:

	v_p_500ms	v_p_400ms	v_p_300ms	v_p_200ms	v_p_100ms	vel_x	curv_p_900ms	curv_p_700ms	curv_p_500ms	curv_p_300ms	curv_p_200ms	curv_p_100ms	curv	curv_f_100ms	curv_f_200ms	curv_f_300ms	curv_f_400ms	curv_f_500ms	curv_f_700ms	curv_f_900ms	act_wheel_rad
kendall	0	0	0	0	0	0	0.95	0.952	0.953	0.954	0.955	0.955	0.956	0.956	0.956	0.955	0.955	0.954	0.953	0.952	1
Spearman	0	0	0	0	0	0	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	1
Pearson	0	0	0	0	0	0	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	1
Covariance	-1.9e-05	1.9e-05	1.8e-05	1.8e-05	1.8e-05	1.8e-05	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1

Correlations – Sine Signal Based Data:

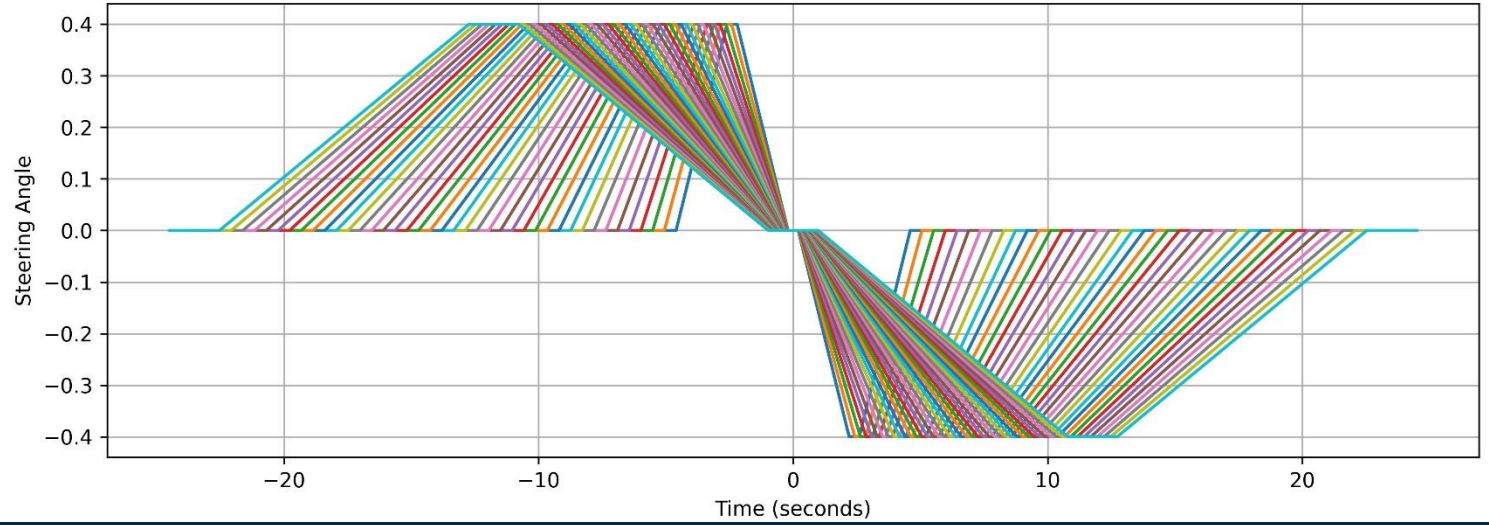
	v_p_500ms	v_p_400ms	v_p_300ms	v_p_200ms	v_p_100ms	vel_x	curv_p_900ms	curv_p_700ms	curv_p_500ms	curv_p_300ms	curv_p_200ms	curv_p_100ms	curv	curv_f_100ms	curv_f_200ms	curv_f_300ms	curv_f_400ms	curv_f_500ms	curv_f_700ms	curv_f_900ms	act_wheel_rad
kendall	0.049	0.048	0.046	0.045	0.043	0.043	0.753	0.791	0.826	0.86	0.876	0.89	0.9	0.904	0.9	0.889	0.873	0.854	0.813	0.771	1
Spearman	0.085	0.083	0.082	0.081	0.08	0.078	0.914	0.937	0.955	0.969	0.974	0.978	0.981	0.981	0.98	0.976	0.971	0.965	0.948	0.925	1
Pearson	0.097	0.096	0.095	0.093	0.092	0.09	0.902	0.931	0.955	0.973	0.98	0.985	0.987	0.988	0.988	0.985	0.98	0.974	0.956	0.932	1
Covariance	0.097	0.096	0.095	0.093	0.092	0.09	0.9	0.93	0.96	0.97	0.98	0.98	0.99	0.99	0.99	0.98	0.98	0.97	0.96	0.93	1

Correlations – Scenario Data:

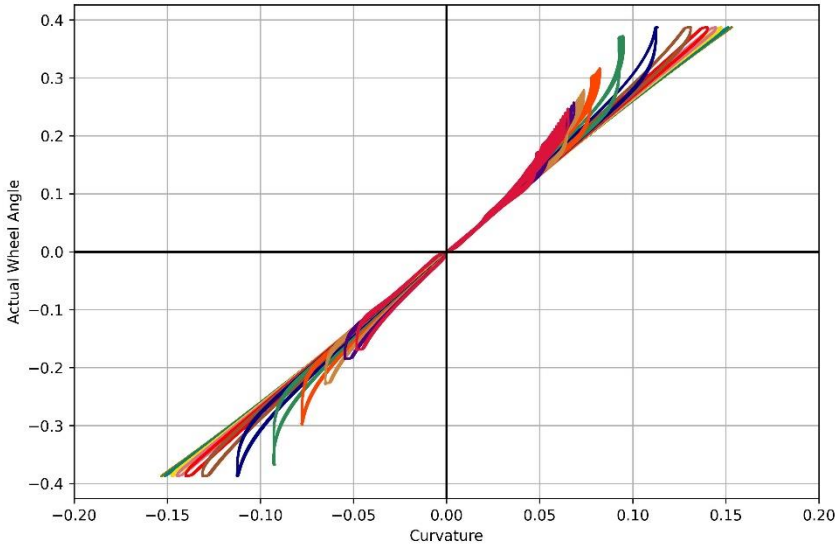
	v_p_500ms	v_p_400ms	v_p_300ms	v_p_200ms	v_p_100ms	vel_x	curv_p_900ms	curv_p_700ms	curv_p_500ms	curv_p_300ms	curv_p_200ms	curv_p_100ms	curv	curv_f_100ms	curv_f_200ms	curv_f_300ms	curv_f_400ms	curv_f_500ms	curv_f_700ms	curv_f_900ms	act_wheel_rad
kendall	-0.009	-0.009	-0.009	-0.009	-0.009	-0.009	0.739	0.798	0.853	0.844	0.857	0.896	0.949	0.967	0.929	0.88	0.846	0.832	0.829	0.787	1
Spearman	0.016	0.016	0.017	0.017	0.017	0.018	0.887	0.925	0.955	0.947	0.951	0.968	0.987	0.996	0.985	0.965	0.948	0.94	0.941	0.918	1
Pearson	-0.026	-0.027	-0.027	-0.027	-0.027	-0.027	0.953	0.97	0.984	0.99	0.993	0.996	0.999	0.999	0.996	0.992	0.988	0.985	0.975	0.959	1
Covariance	-0.026	-0.027	-0.027	-0.027	-0.027	-0.027	0.95	0.97	0.98	0.99	0.99	1	1	1	1	0.99	0.99	0.98	0.97	0.96	1

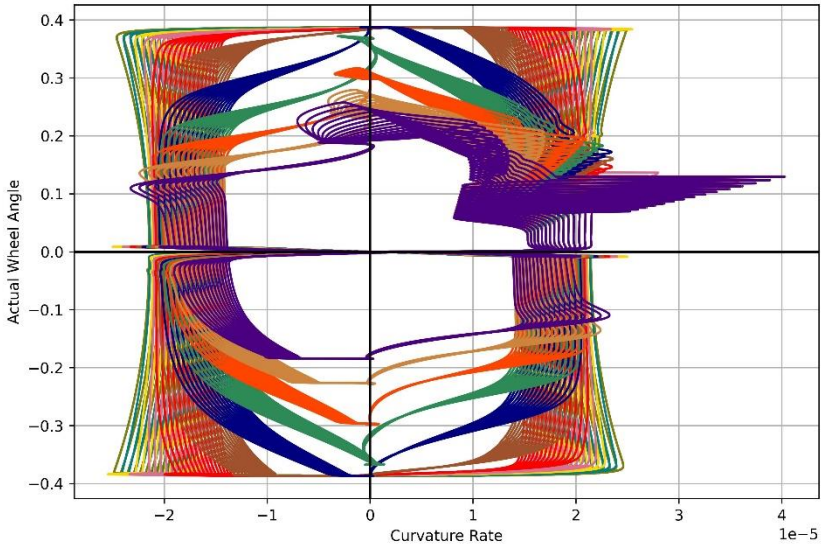
New Data Generation – Extending the State Space (near to horizon)

Possible Steering Ramp Up and Down:

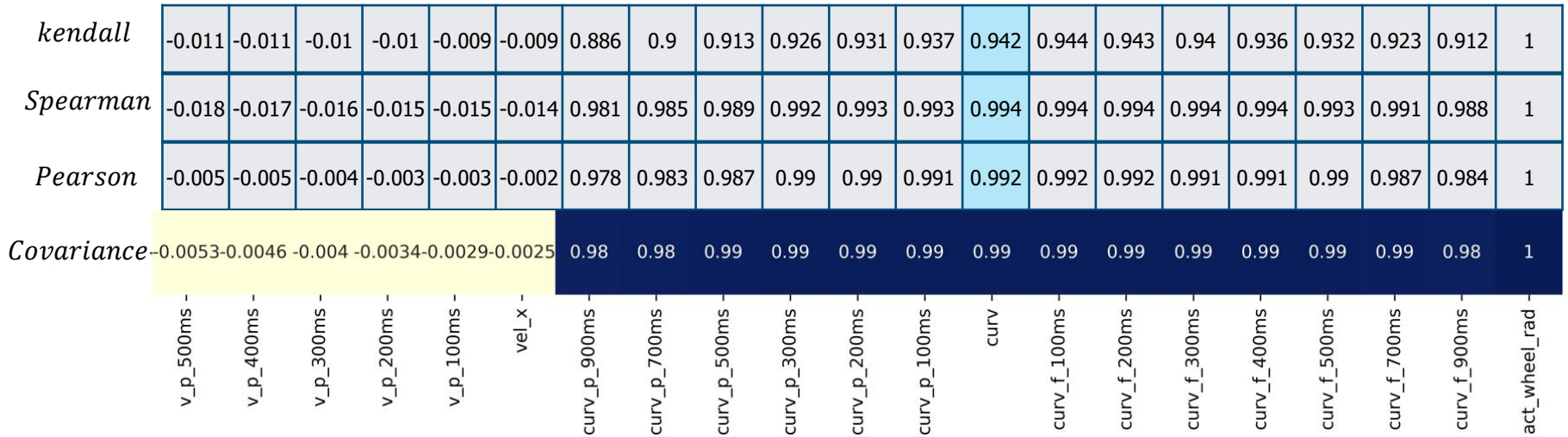


Possible Steering Ramp Up and Down:



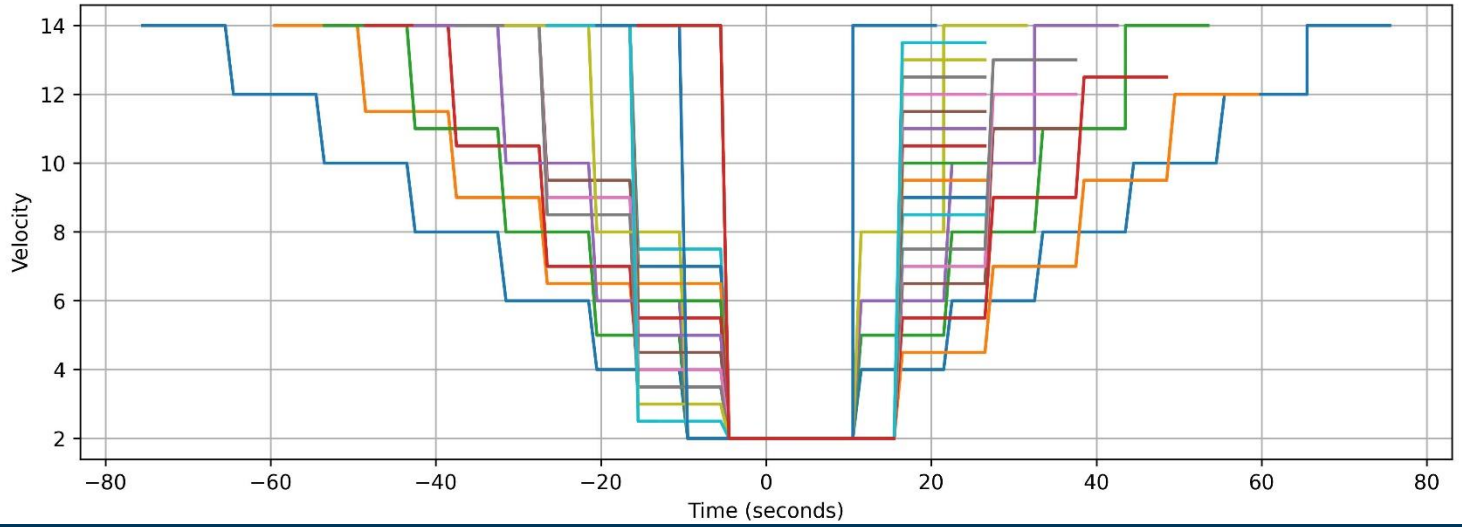


Correlations – Set 1:



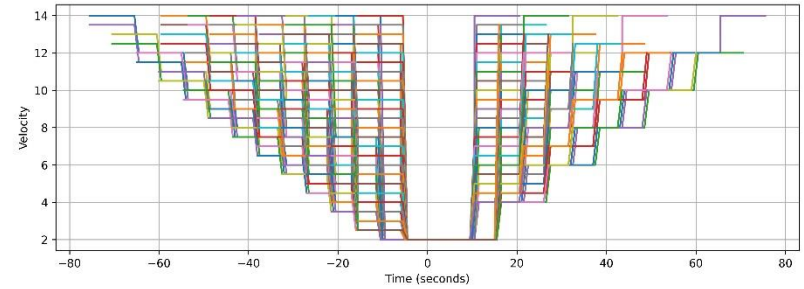
	v_p_500ms	v_p_400ms	v_p_300ms	v_p_200ms	v_p_100ms	vel_x	curv_p_900ms	curv_p_700ms	curv_p_500ms	curv_p_300ms	curv_p_200ms	curv_p_100ms	curv	curv_f_100ms	curv_f_200ms	curv_f_300ms	curv_f_400ms	curv_f_500ms	curv_f_700ms	curv_f_900ms	act_wheel_rad
kendall	-0.011	-0.011	-0.01	-0.01	-0.009	-0.009	0.886	0.9	0.913	0.926	0.931	0.937	0.942	0.944	0.943	0.94	0.936	0.932	0.923	0.912	1
Spearman	-0.018	-0.017	-0.016	-0.015	-0.015	-0.014	0.981	0.985	0.989	0.992	0.993	0.993	0.994	0.994	0.994	0.994	0.994	0.993	0.991	0.988	1
Pearson	-0.005	-0.005	-0.004	-0.003	-0.003	-0.002	0.978	0.983	0.987	0.99	0.99	0.991	0.992	0.992	0.992	0.991	0.991	0.99	0.987	0.984	1
Covariance	-0.0053	-0.0046	-0.004	-0.0034	-0.0029	-0.0025	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	1

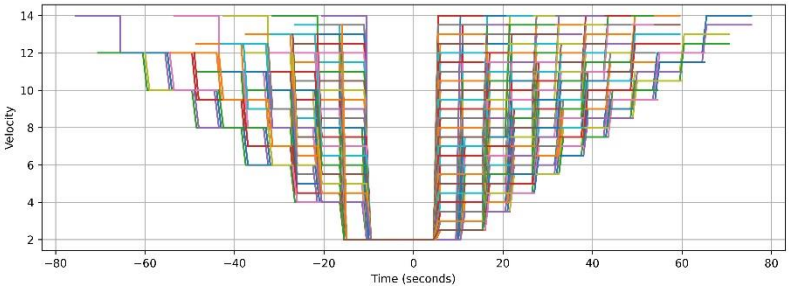
Possible Velocity Step Up and Down:

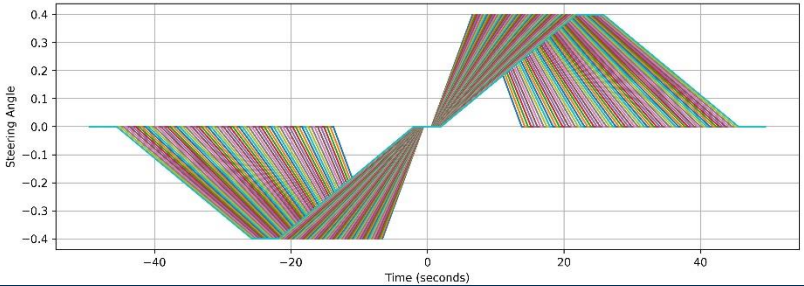


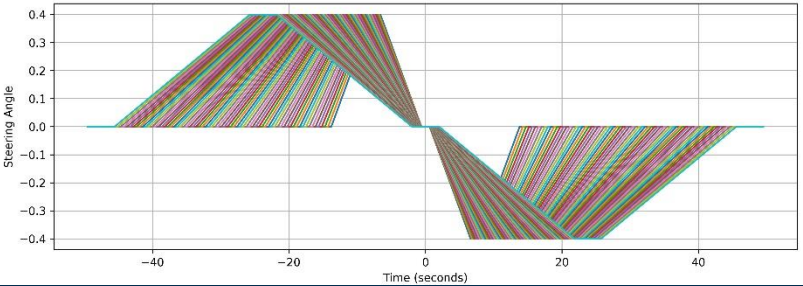
- Velocity will go to new state with $1\ m/s^2$ acceleration currently. This can be treated as a variable in future for further data generation.
- After changes in the velocity, it will be kept for some timespan – as decided by the variable $"time"$

Intensified Possible Velocity Step Up and Down:





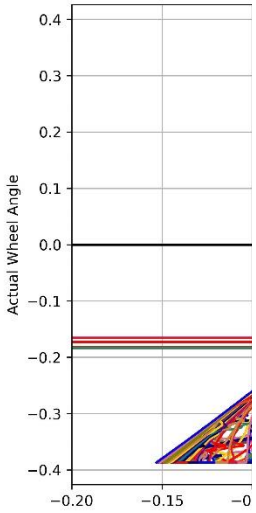


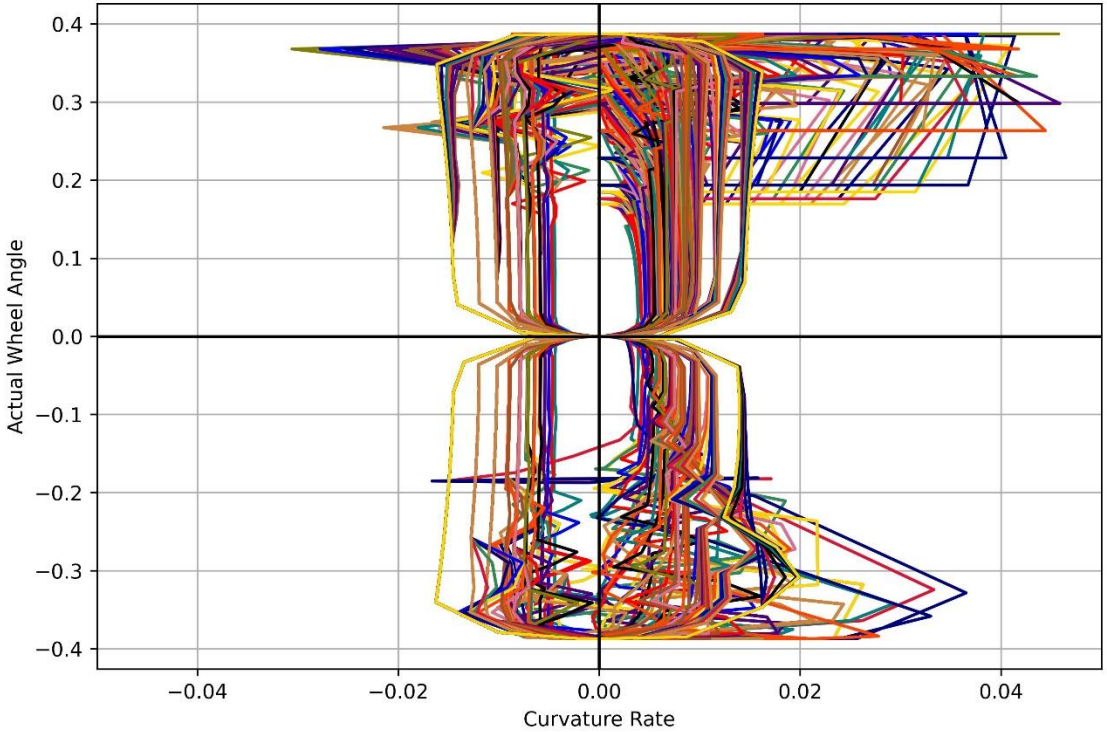


Total Number of Signals : (576 + 576) = 1152

Generated Data for Sharp Step up & Step-Down Signals :

Total Number of Signals : 576





Correlations – Horizon Data:

	v_p_500ms	v_p_400ms	v_p_300ms	v_p_200ms	v_p_100ms	vel_x	curv_p_900ms	curv_p_700ms	curv_p_500ms	curv_p_300ms	curv_p_200ms	curv_p_100ms	curv	curv_f_100ms	curv_f_200ms	curv_f_300ms	curv_f_400ms	curv_f_500ms	curv_f_700ms	curv_f_900ms	act_wheel_rad
kendall	0.121	0.117	0.114	0.11	0.106	0.102	0.927	0.936	0.944	0.951	0.954	0.956	0.958	0.957	0.955	0.953	0.95	0.946	0.939	0.931	1
Spearman	0.144	0.138	0.132	0.126	0.12	0.114	0.992	0.993	0.995	0.995	0.996	0.996	0.996	0.996	0.996	0.996	0.995	0.995	0.994	0.993	1
Pearson	0.106	0.101	0.095	0.089	0.083	0.078	0.991	0.993	0.994	0.995	0.995	0.995	0.996	0.996	0.995	0.995	0.995	0.995	0.994	0.992	1
Covariance	0.11	0.1	0.095	0.089	0.083	0.078	0.99	0.99	0.99	0.99	1	1	1	1	1	1	0.99	0.99	0.99	0.99	1

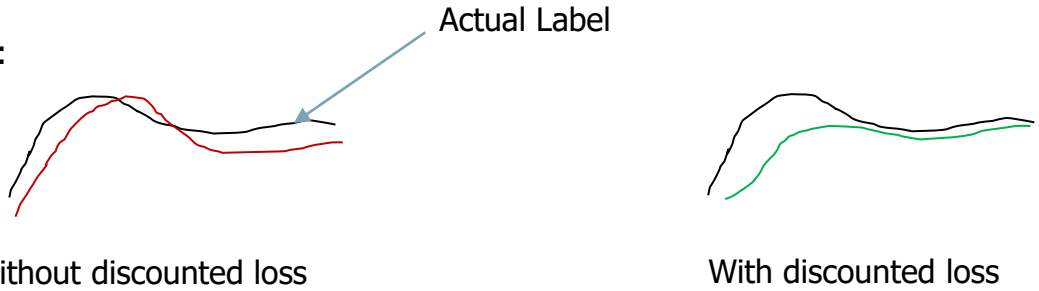
Discounted Loss Function:

- Since, we are much care about required final signal, the loss function is given by discounted parameters ($generally\ 0.95 < \gamma < 0.99$)

$$L(\theta) = e_t + \gamma e_{t-1} + \gamma^2 e_{t-2} + \cdots + (upto\ final\ lookback)$$

Y _actual = 5 * 1

Expected :



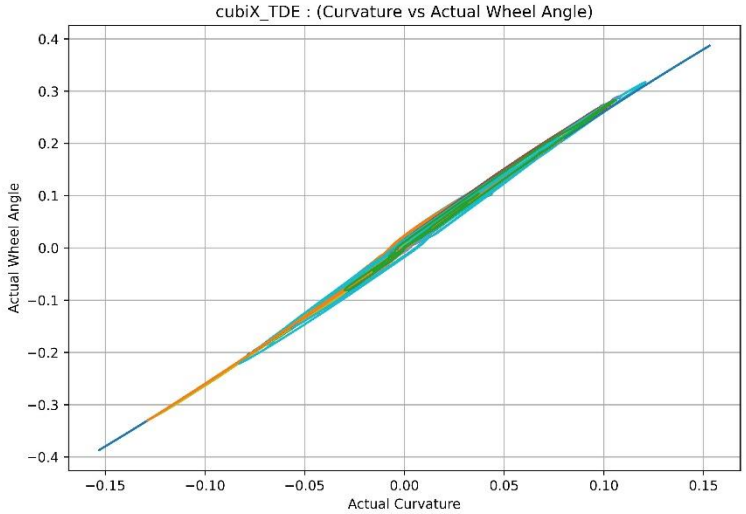
Without discounted loss

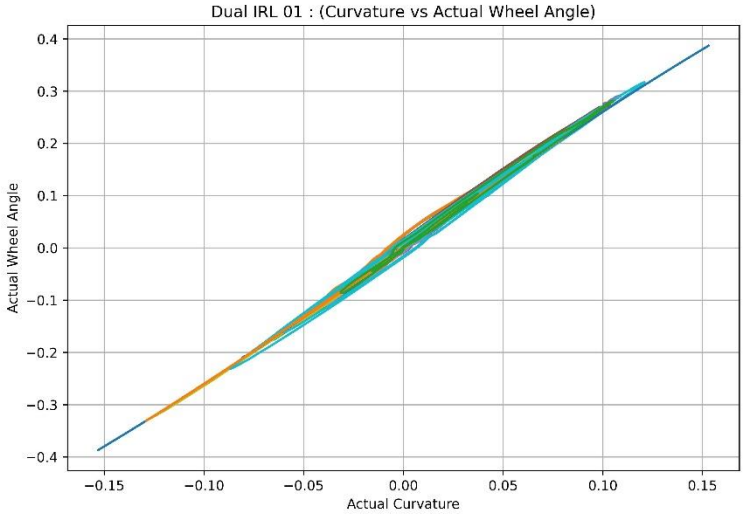
With discounted loss

- Number of Lookbacks ?
  - Based on the maximum acceleration/ deceleration value, we can choose the value. (i.e $a = 0.5\frac{m}{s^2}$, then lookbacks should be 20)

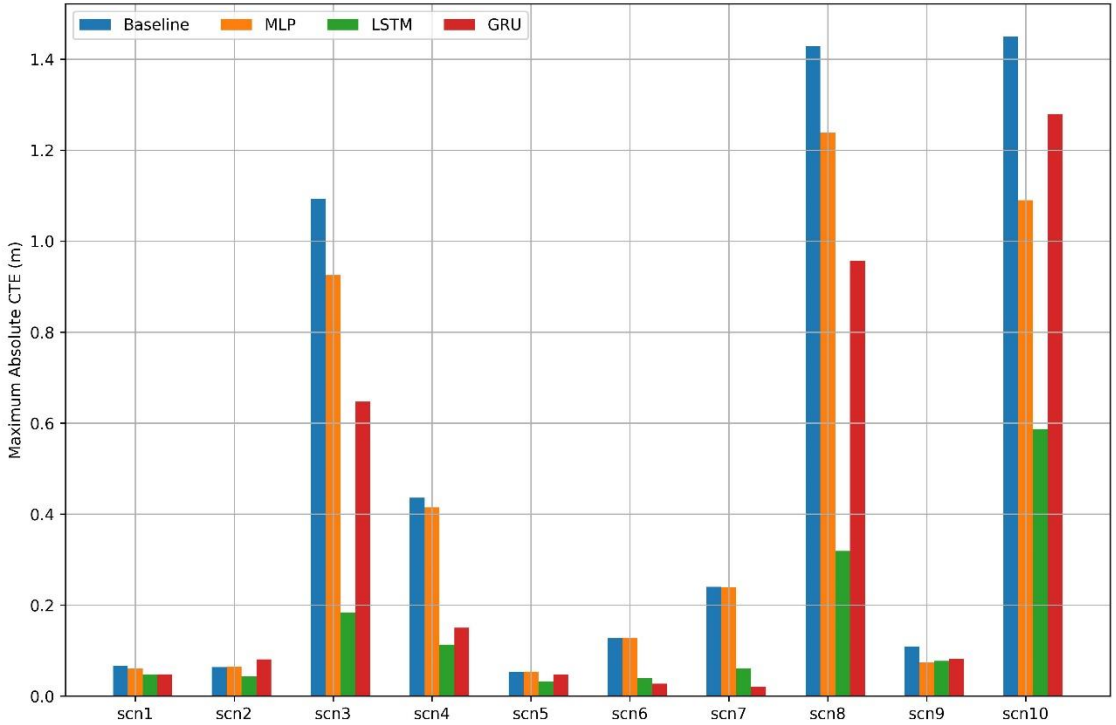
Model Training by Revised New Data

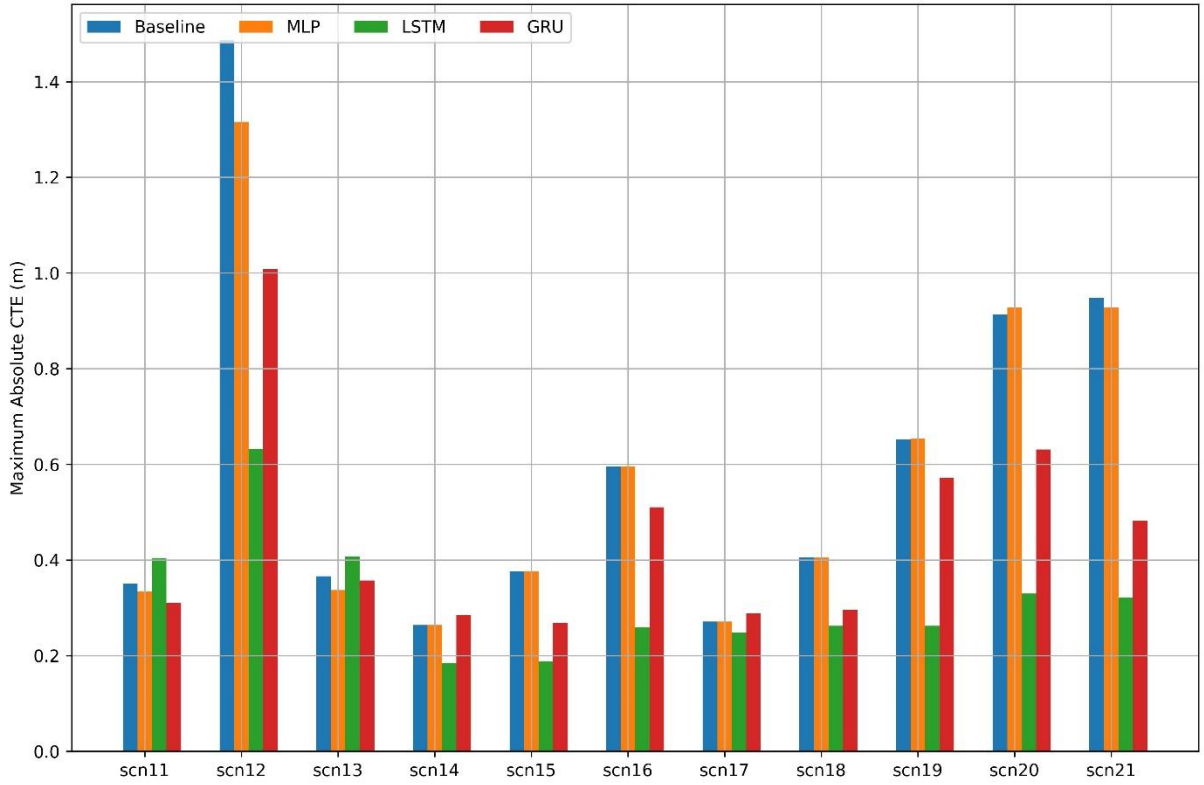
Data generated through FMU by various controller's scenario signals

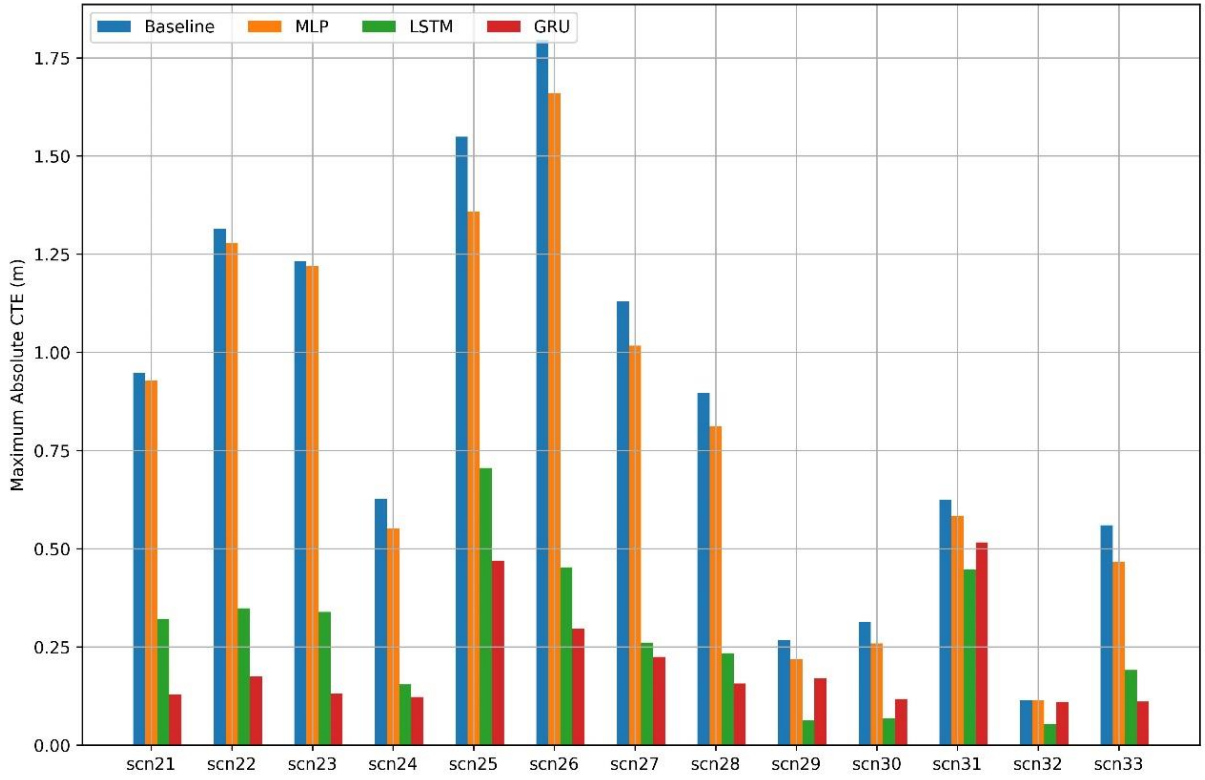




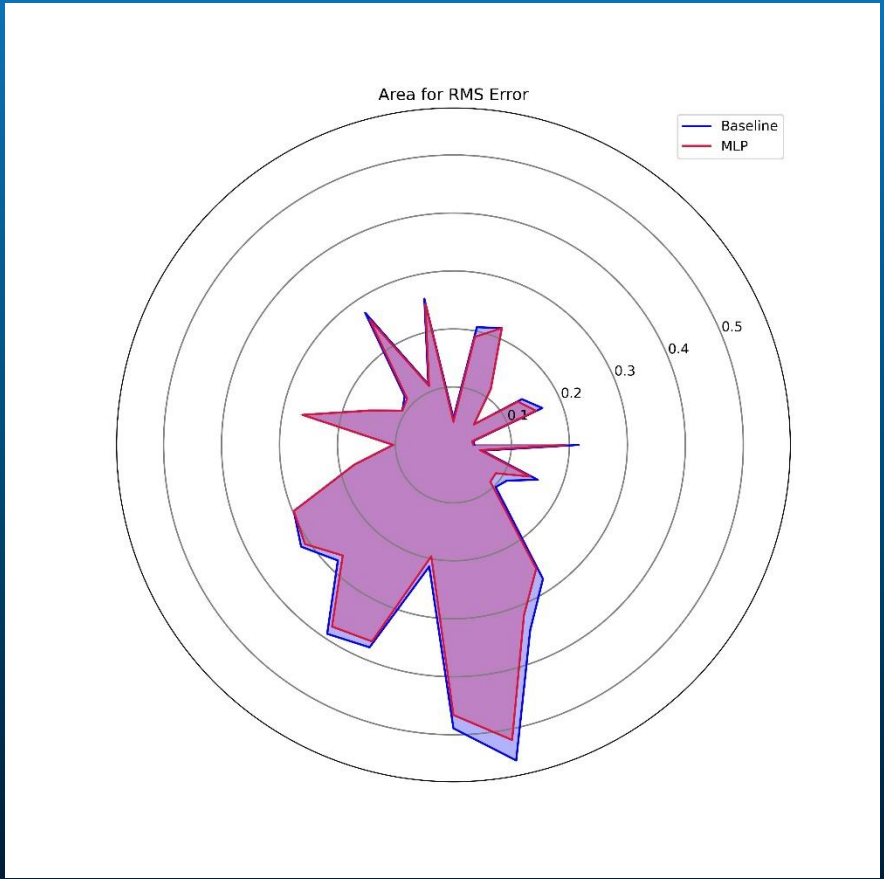
Pipeline Results Comparison 01 – Maximum Absolute CTE



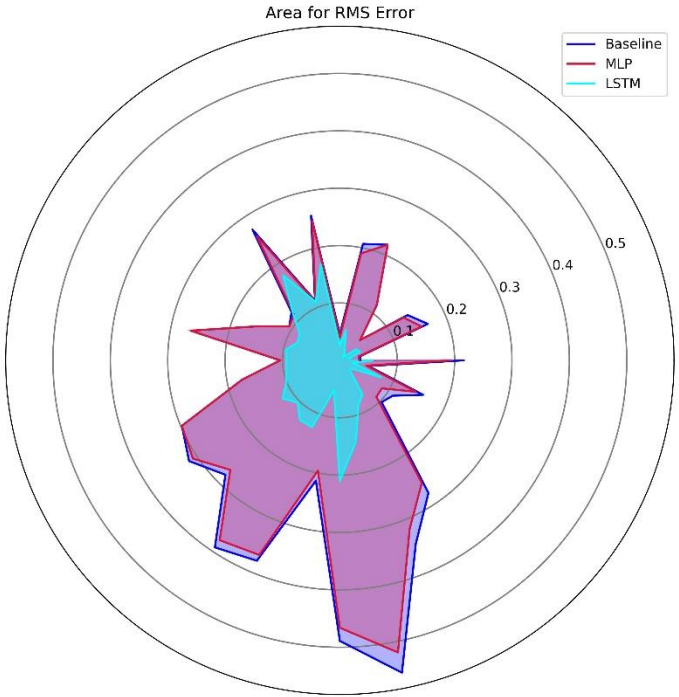


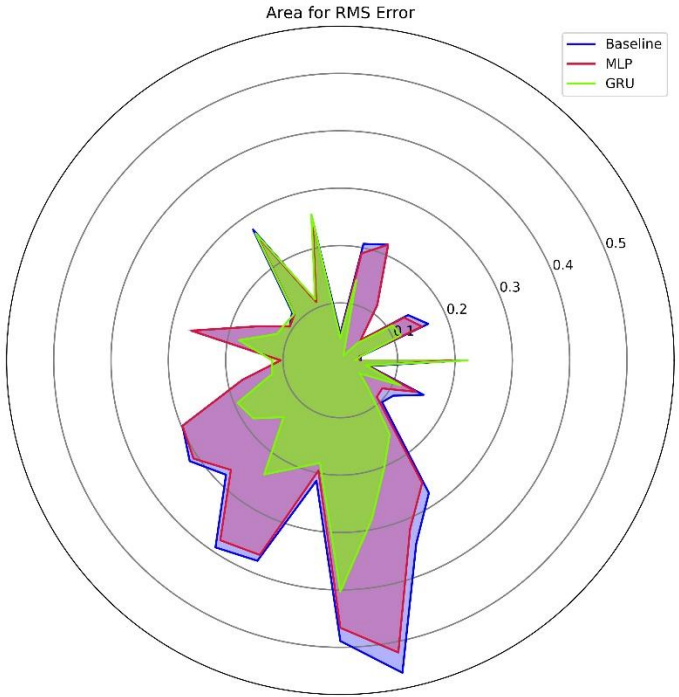


RMS Value of CTE 01 – Polar Plot



RMS Value of CTE 02 – Polar Plot





Results Comparison in Pipeline Assessment – Max CTE

Testing Scenario	Kinematic_Model	MLP_model	LSTM_model	GRU_model
uturn r10m 10kph s n	0.066	0.06	0.047	0.048
infty 10_15kph s n	0.064	0.065	0.043	0.081
fasttrack plant2 v1 s n	1.093	0.925	0.184	0.647
fasttrack plant2 v2 s n	0.436	0.415	0.113	0.15
circle r10m 10kph s n	0.054	0.054	0.032	0.047
circle r20m 20kph s n	0.127	0.127	0.039	0.027
circle r50m 30kph s n	0.24	0.239	0.061	0.021
fasttrack plant2 v1 r n	1.428	1.238	0.319	0.957
infty 10_15kph r n	0.109	0.074	0.077	0.082
fasttrack plant2 v1 s w	1.449	1.09	0.587	1.279

Pipeline assessment has totally 33 different scenarios and developed models are compared against baseline controller with all scenarios. The mean of all scenario's error are computed as below.

Mean of Errors :	**0.670**	**0.613**(8.5%)	**0.252**(62.3%)	**0.437**(34.78%)

Results Comparison in Pipeline Assessment – RMS Value

Testing Scenario	Kinematic_Model	MLP_model	LSTM_model	GRU_model
uturn r10m 10kph s n	0.036	0.034	0.019	0.026
infty 10_15kph s n	0.036	0.033	0.016	0.036
fasttrack plant2 v1 s n	0.166	0.154	0.038	0.114
fasttrack plant2 v2 s n	0.142	0.134	0.035	0.11
circle r10m 10kph s n	0.05	0.05	0.007	0.042
circle r20m 20kph s n	0.116	0.116	0.015	0.01
circle r50m 30kph s n	0.218	0.218	0.022	0.017
fasttrack plant2 v1 r n	0.207	0.19	0.054	0.143
infty 10_15kph r n	0.046	0.04	0.026	0.038
fasttrack plant2 v1 s w	0.257	0.248	0.17	0.259

Pipeline assessment has totally 33 different scenarios and developed models are compared against baseline controller with all scenarios. The mean of all scenario's error are computed as below.

Mean of Errors :	0.205	0.195(4.9%)	0.078(61.9%)	0.139(32.2%)

LSTM vs LSTM (discounted loss model)

Comparison between LSTM and Discounted LSTM - Max CTE

Testing Scenario	Kinematic_Model	LSTM_Dis_Model	LSTM_model
uturn r10m 10kph s n	0.066	0.05	0.047
infty 10_15kph s n	0.064	0.063	0.043
fasttrack plant2 v1 s n	1.093	0.466	0.184
fasttrack plant2 v2 s n	0.436	0.101	0.113
circle r10m 10kph s n	0.054	0.049	0.032
circle r20m 20kph s n	0.127	0.049	0.039
circle r50m 30kph s n	0.24	0.045	0.061
fasttrack plant2 v1 r n	1.428	0.777	0.319
infty 10_15kph r n	0.109	0.065	0.077
fasttrack plant2 v1 s w	0.951	0.647	0.587

Pipeline assessment has totally 33 different scenarios and developed models are compared against baseline controller with all scenarios. The mean of all scenario's error are computed as below.

Mean of Errors :	0.670	0.379(43.43%)	0.252(62.3%)

Comparison between LSTM and Discounted LSTM - RMS Value

Testing Scenario	Kinematic_Model	LSTM_Dis_Model	LSTM_model
uturn r10m 10kph s n	0.036	0.019	0.028
infty 10_15kph s n	0.036	0.016	0.031
fasttrack plant2 v1 s n	0.166	0.038	0.06
fasttrack plant2 v2 s n	0.142	0.035	0.032
circle r10m 10kph s n	0.05	0.007	0.044
circle r20m 20kph s n	0.116	0.015	0.027
circle r50m 30kph s n	0.218	0.022	0.037
fasttrack plant2 v1 r n	0.207	0.054	0.1
infty 10_15kph r n	0.046	0.026	0.033
fasttrack plant2 v1 s w	0.232	0.17	0.186

Pipeline assessment has totally 33 different scenarios and developed models are compared against baseline controller with all scenarios. The mean of all scenario's error are computed as below.

Mean of Errors :	0.205	0.116(43.41%)	0.078(61.9%)

Next ? – Hyper Parameter Tuning

- Hyperparameter Tuning
  - Lookup window
  - Learning rate in the optimizer
  - Network Architecture Investigation

- Experiments