Vehicle Trajectory Prediction based on Motion Model and Maneuver Recognition

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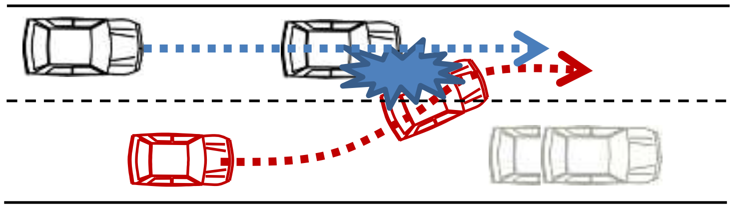
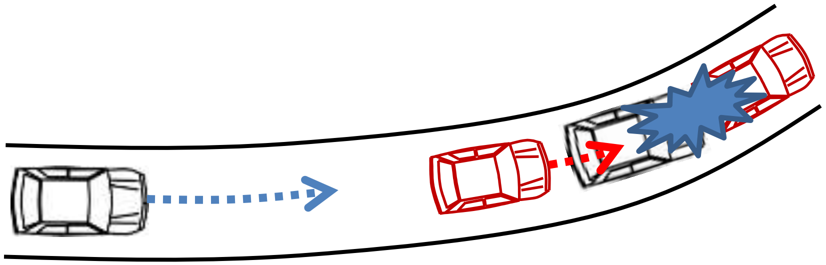
Context

- Trajectory prediction is a necessary task for collision avoidance/warning systems (CAS/CWS)
- It is not a deterministic task since it depends on the driver's will and on a lot of parameters that are not all measured or even always considered
- Assumptions about the vehicle's movement or considerations about driving maneuvers can help to approximate the future positions of the vehicle, for the next few seconds.

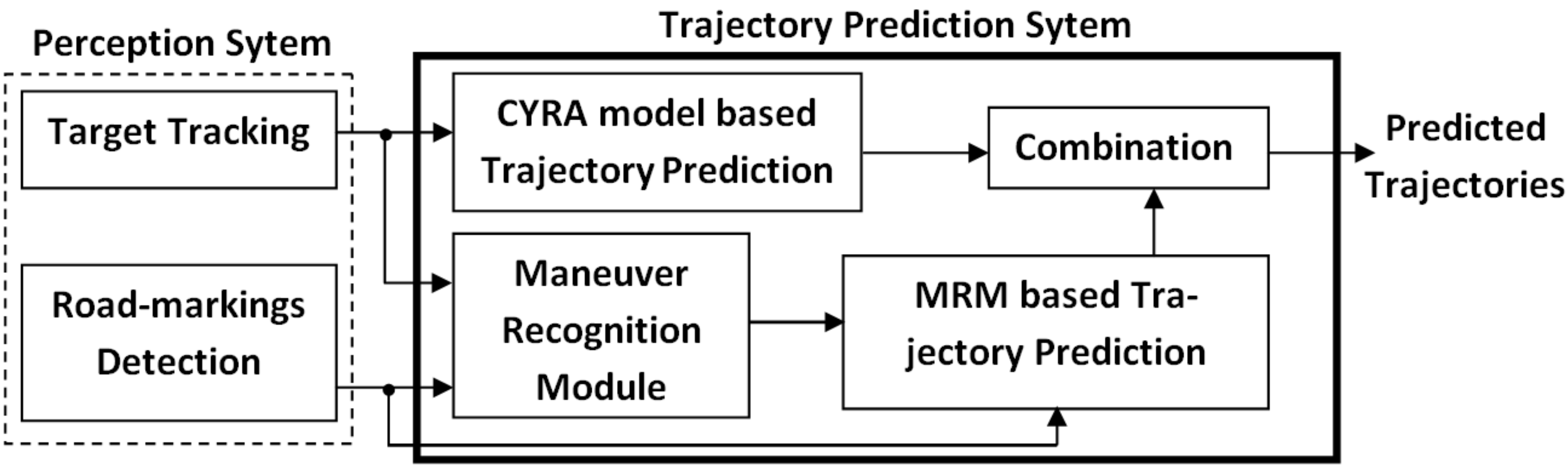


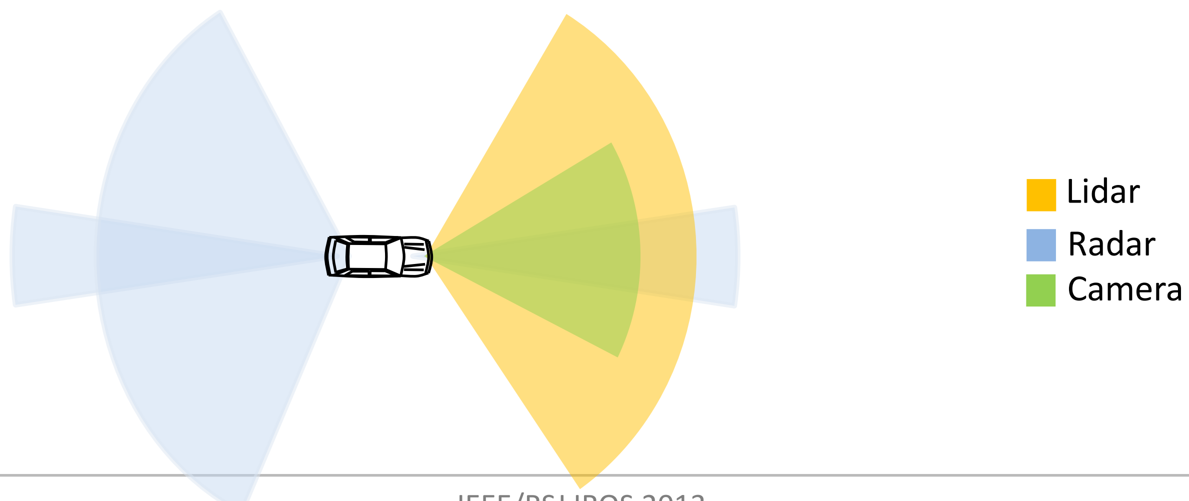


Objective

- Predict the trajectory of any traffic participant (ego-vehicle or tracked vehicles) for a few seconds, based on:
  - Results of a Tracking System
    - State $\zeta = [x, y, \theta, v, a, \omega]^T$ (in a fixed Cartesian frame)
    - Covariance matrix Σ
  - Road geometry detection
    - Equation of lane marking lines $y=f(x)$
    - Lane width
  - A priori knowledge
    - Motion Model
    - Limited number of lane-related driving maneuvers

System overview

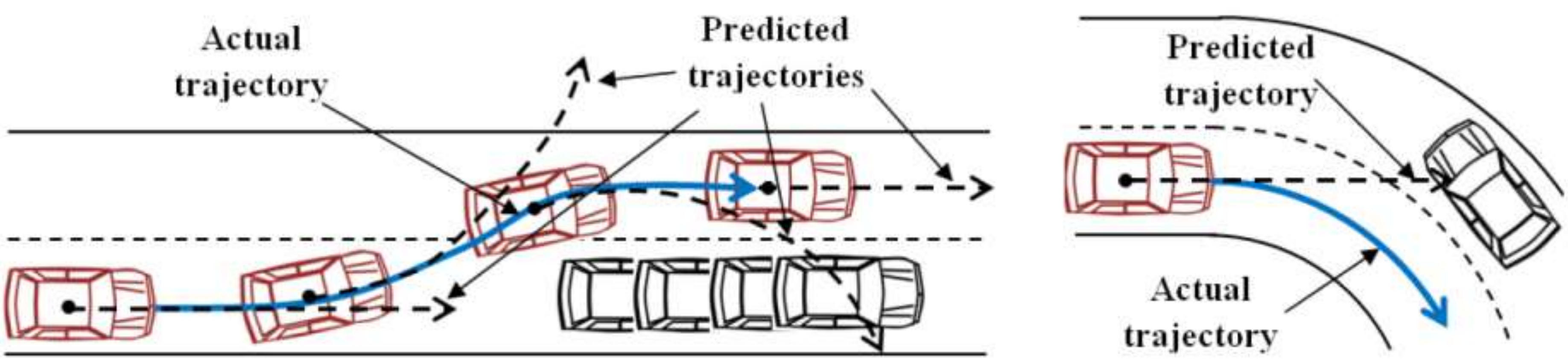




Kinematic-based prediction

- Constant Yaw Rate and Acceleration motion

$$T_{mdl} = \begin{cases} x(t) = & \frac{a_0}{\omega_0^2} cos(\theta(t)) + \frac{v(t)}{\omega_0} sin(\theta(t)) + c_x \\ y(t) = & \frac{a_0}{\omega_0^2} sin(\theta(t)) - \frac{v(t)}{\omega_0} cos(\theta(t)) + c_y \end{cases}$$



(a) Lane changing (b) Entering a bend

Poor long-term prediction performance

Road-based prediction

- To exploit the knowledge of the road shape
  - Straight road, curve, etc.
- Trajectory depends on the maneuvers
- A maneuver Recognition module is mandatory

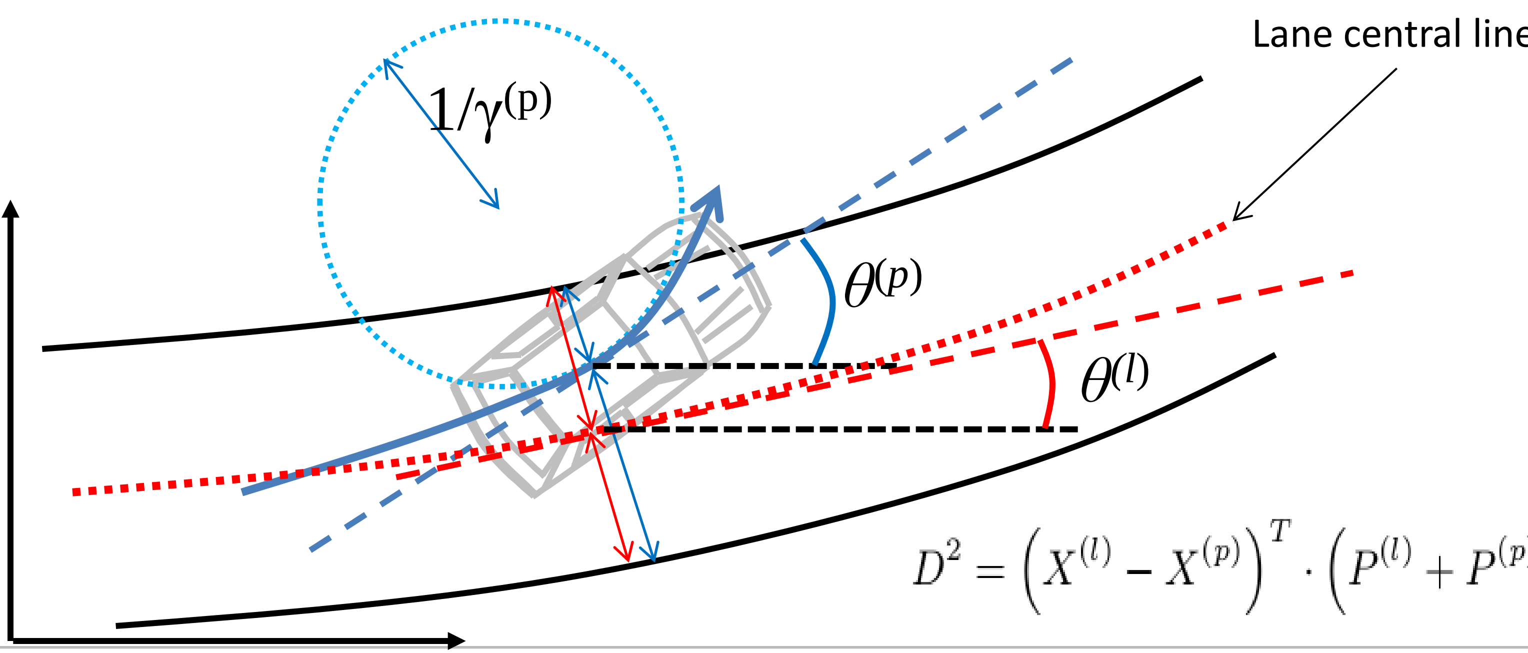
- Basic idea
  - Measure the lane shape
  - Quantify the adequacy between the movement and the lane shape

Maneuver Recognition

- Model of the vehicle local trajectory and road central line with the same state vector

$$X^{(p)} = [d_l, d_r, \theta, \gamma]^T \qquad \gamma = \frac{\omega}{v}$$

$$X^{(l)} = [d_l, d_r, \theta, \gamma]^T$$

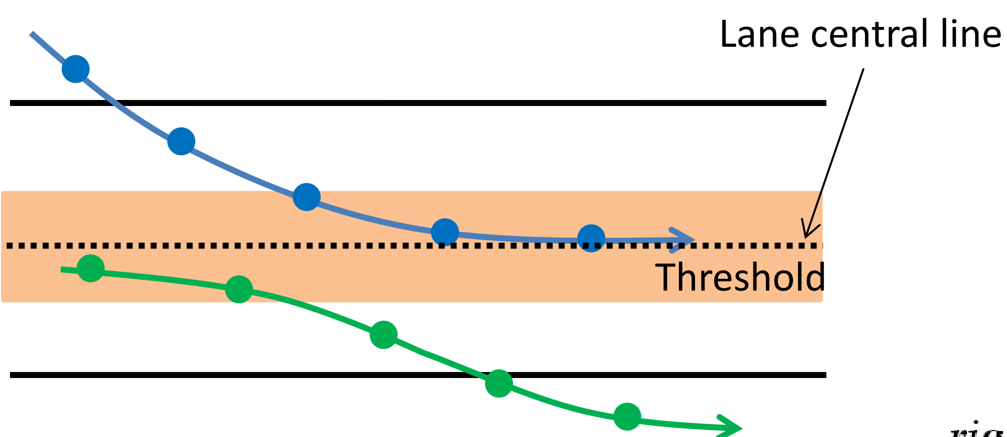


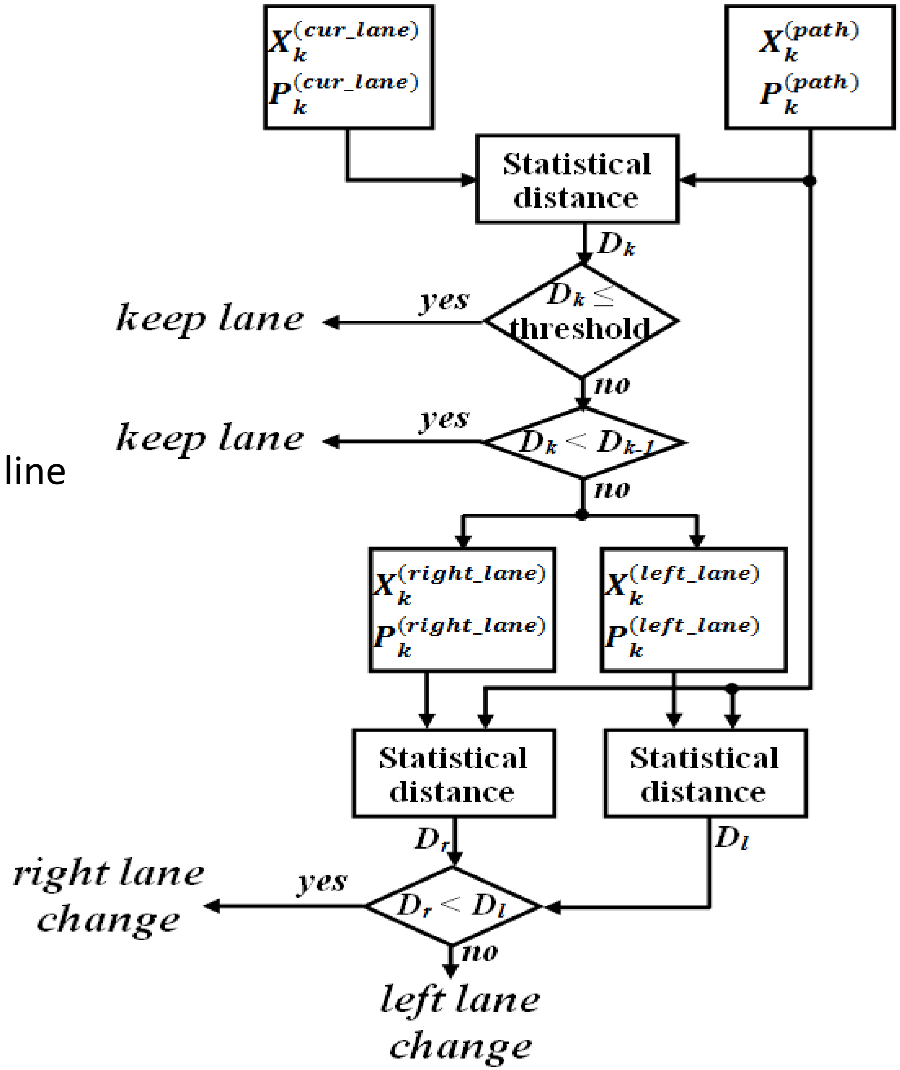
$$D^2 = \left(X^{(l)} - X^{(p)}\right)^T \cdot \left(P^{(l)} + P^{(p)}\right)^{-1} \cdot \left(X^{(l)} - X^{(p)}\right)$$

Maneuver Recognition (MR)

Two basic maneuvers:

- *keep lane*
- *change lane*



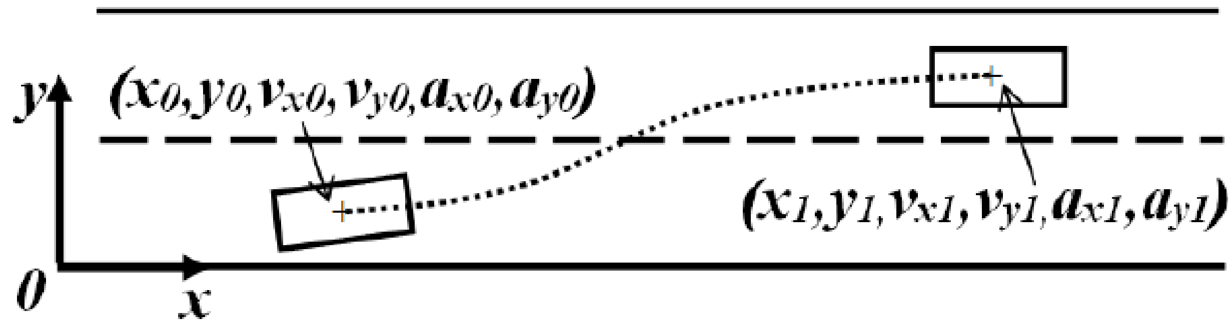


MR based Prediction

- Model longitudinal et lateral components with polynomials

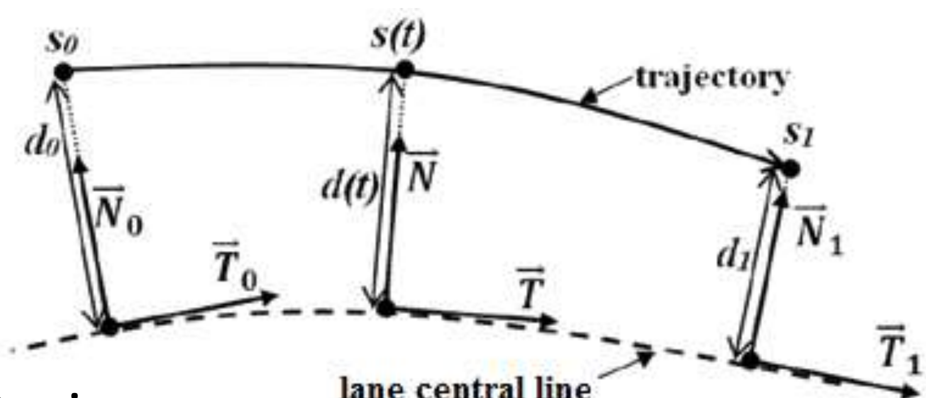
$$x(t) = P_x^{(5)}(t)$$

$$y(t) = P_y^{(5)}(t)$$



- Frenet frame computations for curved roads

$$d(t) = c_5 t^5 + c_4 t^4 + c_3 t^3 + c_2 t^2 + c_1 t + c_0$$



- Conversion back to the Cartesian space

MR based Prediction

- Initial conditions are known from tracking results
- Final conditions are known assuming
  - Constant longitudinal acceleration during maneuver
  - Maneuver ends on the central line of intended lane

$$\begin{cases} d_0 &= d_0^* \\ \dot{d}_0 &= v_0 sin\left(\theta_0 - \theta_{\vec{T_0}}\right) \\ \ddot{d}_0 &= \sqrt{(a_0^2 + \gamma_0 v_0^2)} sin\left(\theta_0 - \theta_{\vec{T_0}}\right) \\ s_0 &= 0 \\ \dot{s}_0 &= v_0 cos\left(\theta_0 - \theta_{\vec{T_0}}\right) \\ \ddot{s}_0 &= \sqrt{(a_0^2 + \gamma_0 v_0^2)} cos\left(\theta_0 - \theta_{\vec{T_0}}\right) \end{cases}$$

$$\begin{cases} d_1 &= d_1^* \\ \dot{d}_1 &= 0 \\ \ddot{d}_1 &= 0 \\ \ddot{s}_1 &= a_0 \end{cases}$$

$$\dot{s}_1 = v_0 + a_0 \cdot t_1$$

$$t_1 = \left\{t^{(i)}\right\}_{i=1..K}$$

$$t^{(K)} \approx 6sec$$

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Polynomial parameters computation

$$d(t) = a_5 t^5 + a_4 t^4 + a_3 t^3 + a_2 t^2 + a_1 t + a_0$$

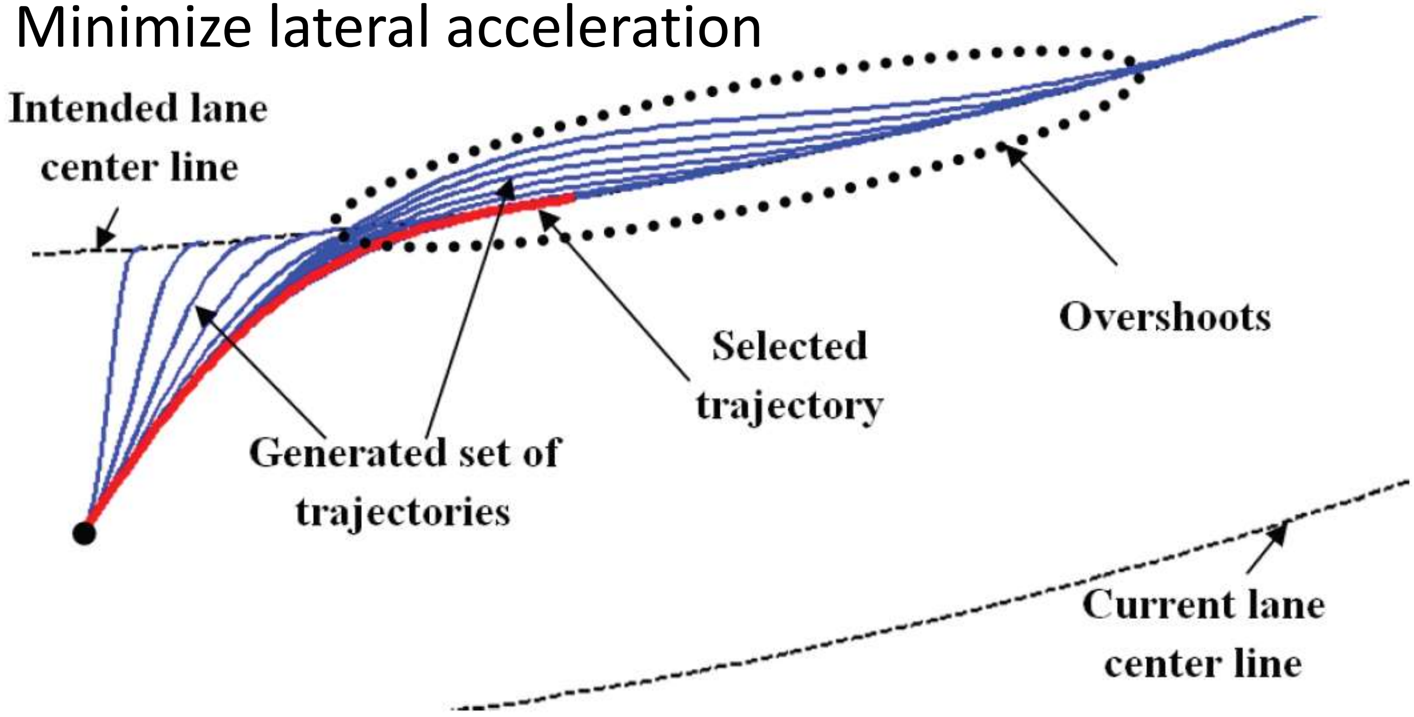
$$\begin{bmatrix} t_0^5 & t_0^4 & t_0^3 & t_0^2 & t_0^1 & 1 \\ t_1^5 & t_1^4 & t_1^3 & t_1^2 & t_1^1 & 1 \\ 5t_0^4 & 4t_0^3 & 3t_0^2 & 2t_0^1 & 1 & 0 \\ 5t_1^4 & 4t_1^3 & 3t_1^2 & 2t_1^1 & 1 & 0 \\ 20t_0^3 & 12t_0^2 & 6t_0^1 & 2 & 0 & 0 \\ 20t_1^3 & 12t_1^2 & 6t_1^1 & 2 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} a_5 \\ a_4 \\ a_3 \\ a_2 \\ a_1 \\ a_0 \end{bmatrix} = \begin{bmatrix} d_0 \\ d_1 \\ \dot{d}_0 \\ \dot{d}_1 \\ \ddot{d}_0 \\ \ddot{d}_1 \end{bmatrix}$$

$$s(t) = a_4 t^4 + a_3 t^3 + a_2 t^2 + a_1 t + a_0$$

$$\begin{bmatrix} t_0^4 & t_0^3 & t_0^2 & t_0^1 & 1 \\ 4t_0^3 & 3t_0^2 & 2t_0^1 & 1 & 0 \\ 4t_1^3 & 3t_1^2 & 2t_1^1 & 1 & 0 \\ 12t_0^2 & 6t_0^1 & 2 & 0 & 0 \\ 12t_1^2 & 6t_1^1 & 2 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} a_4 \\ a_3 \\ a_2 \\ a_1 \\ a_0 \end{bmatrix} = \begin{bmatrix} s_0 \\ \dot{s}_0 \\ \dot{s}_1 \\ \ddot{s}_0 \\ \ddot{s}_1 \end{bmatrix}$$

MR based Prediction

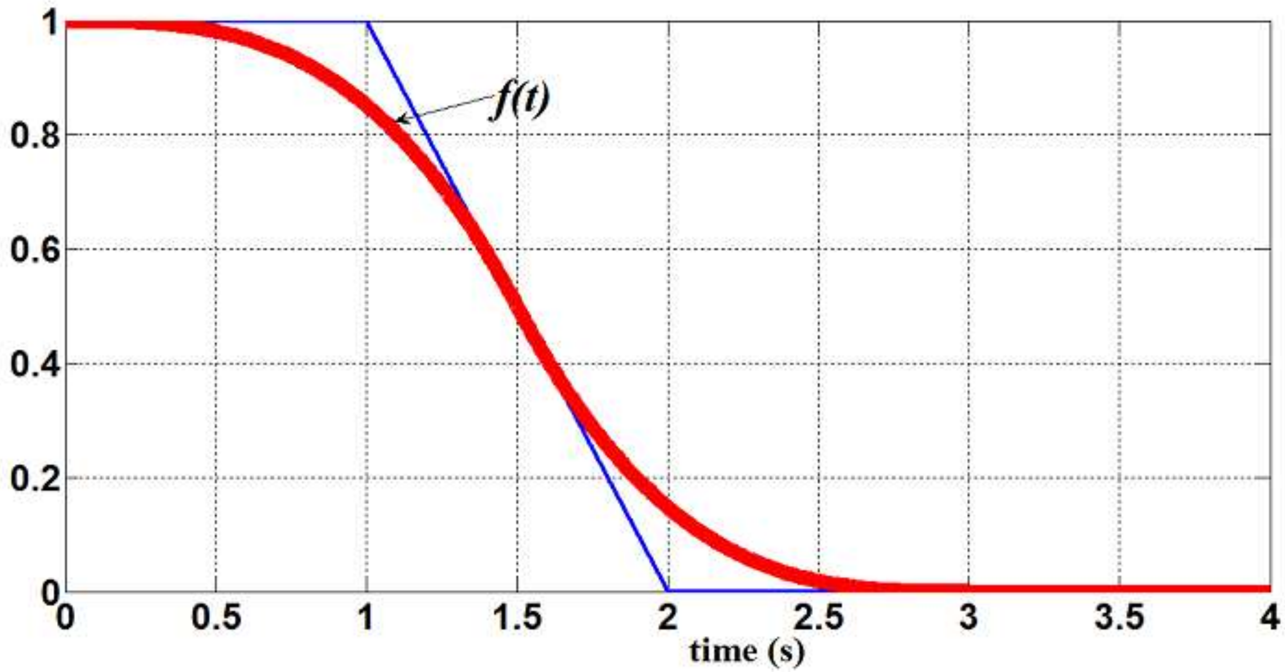
- Trajectory set generation
- Best trajectory selection w.r.t a cost function
  - Minimize duration
  - Minimize lateral acceleration



Final prediction

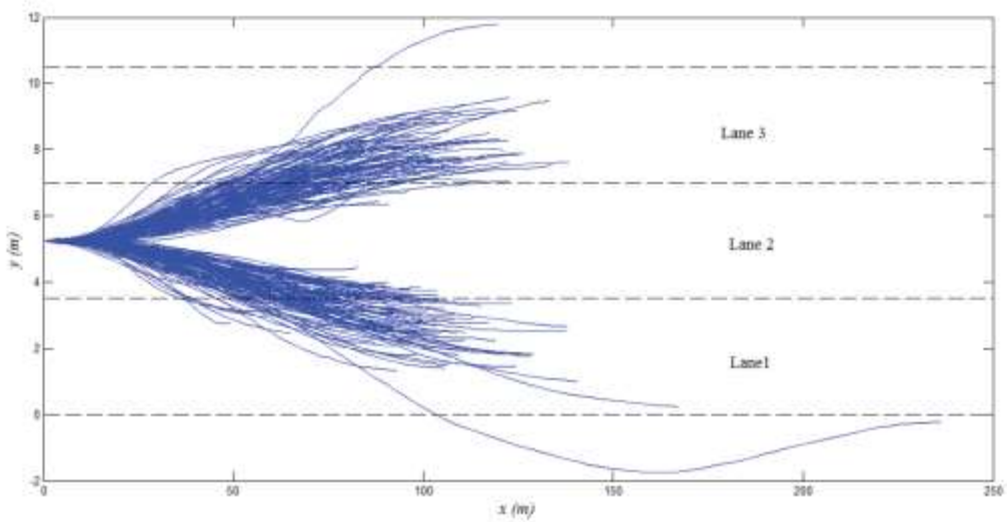
- Combine motion model based prediction (T_{mdl}) and MR based prediction (T_{man})

$$T_{fin} = f(t).T_{mdl} + (1-f(t)).T_{man}$$

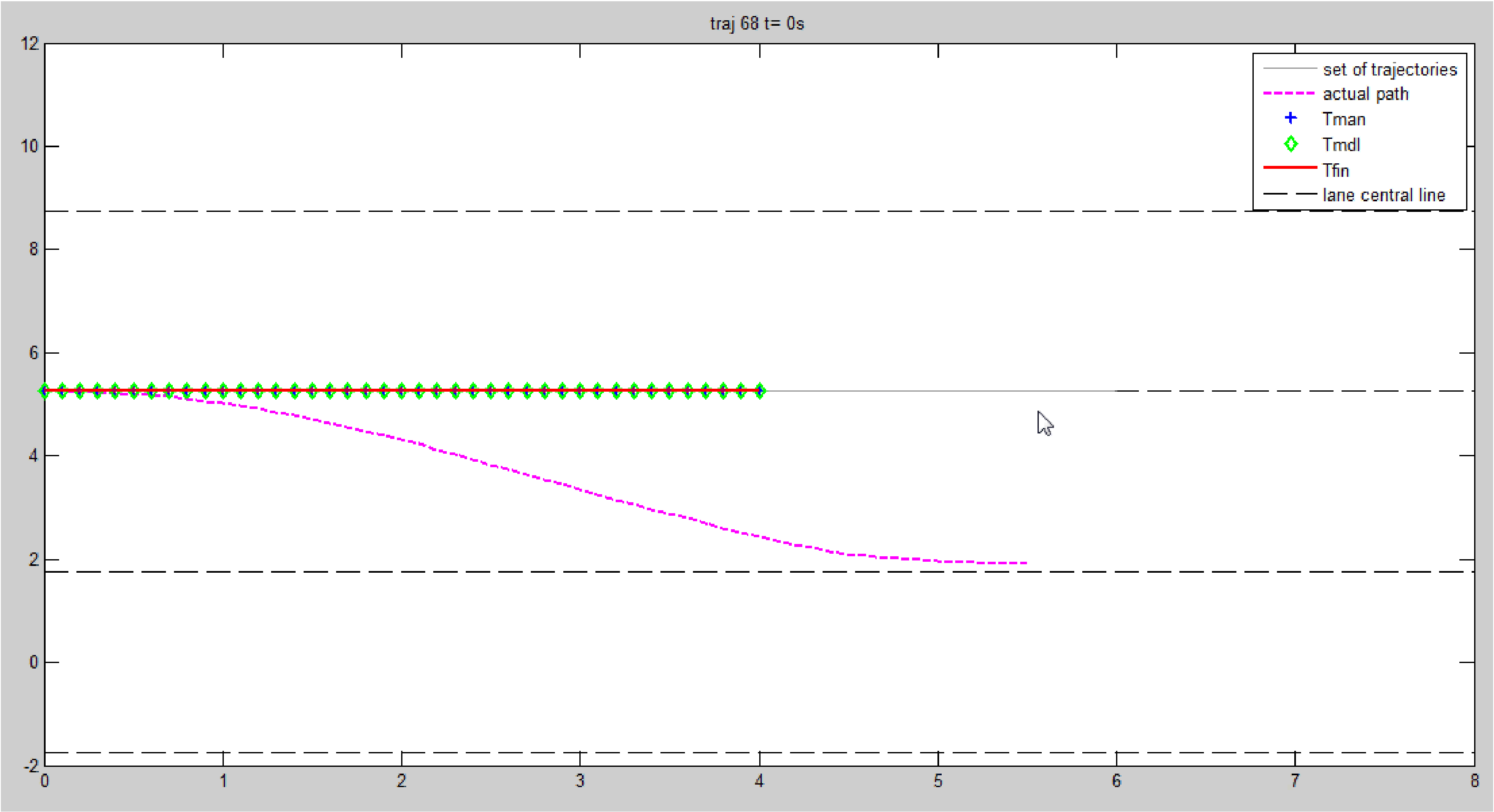


Experimental results

- Human driving data in semi-urban conditions
  - Drivers were asked to change lanes or to overtake other vehicles when possible, on straight road portions
  - 80km/h
- Lane change maneuvers extraction done by Yao Wen' software [W. Yao et al, IV 2012]
- 234 maneuvers
  - 91 right lane changes
  - 119 left lane changes
  - 24 unknown

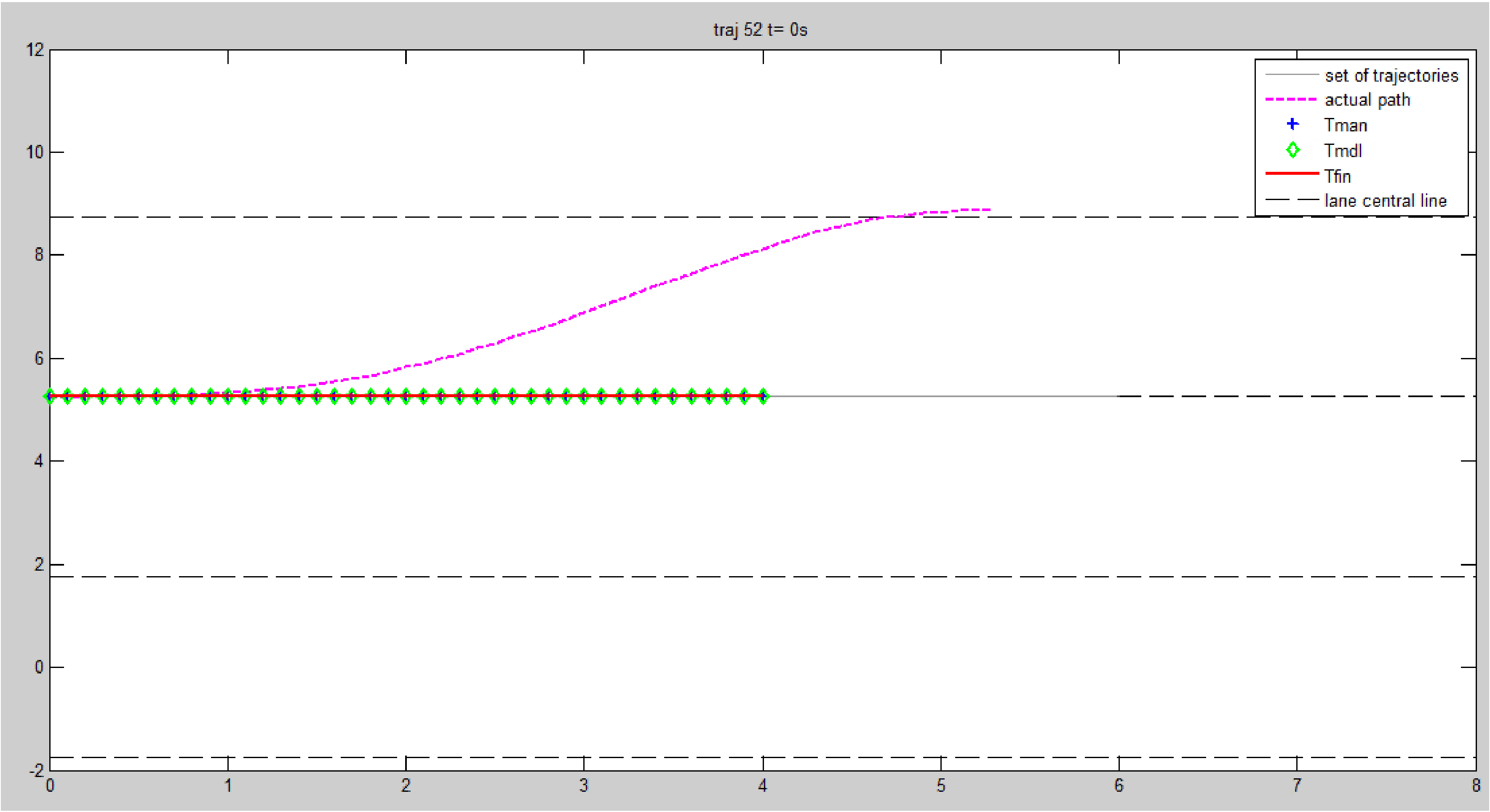


Right lane change



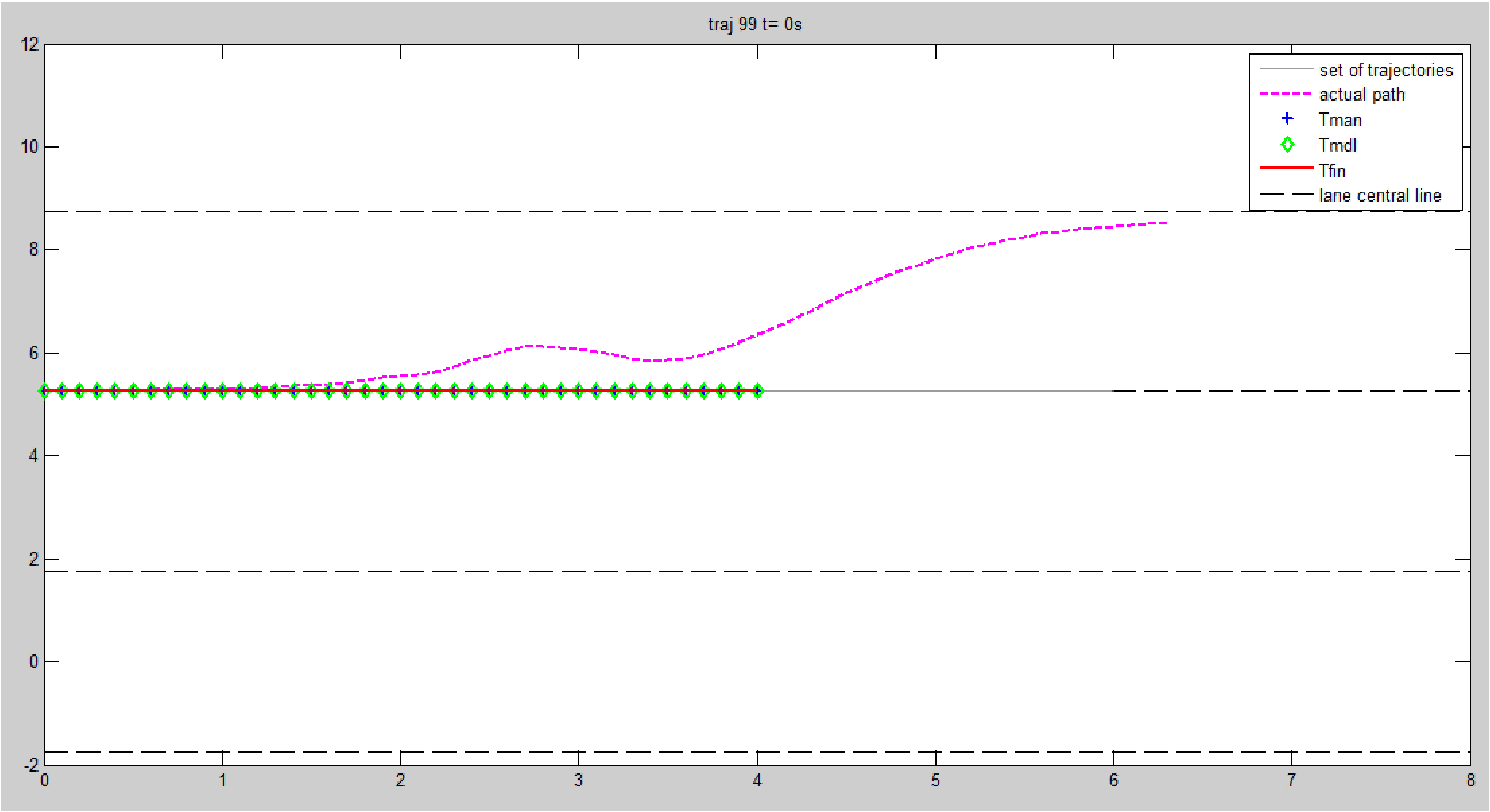
Real data

Left lane change



Real data

Driver hesitating



Real data

Lane change maneuver statistics

- 234 maneuvers

	LLC	RLC
Detection	100%	100%
Mean time before detection	1.15s	1.09
Mean lateral offset before detection	0.3m	0.33m

- Mean time of a lane change = 4s
- Lane changes are detected at 25% of their total length

Accuracy of the trajectory predictions

- Prediction wrt real trajectory mean Euclidean error for different time horizons

	$[0s, 1s[$	$[1s, 2s[$	$[2s, 3s[$	$[3s, 4s[$
T_{mdl}	0.1m	0.49m	2.3m	4.31m
T_{man}	0.15m	0.2m	0.33m	0.45m
T_{fin}	0.09m	0.17m	0.28m	0.45m

- The mixing of the two approaches significantly improves the prediction in the intermediate phase

Conclusion

- A deterministic and efficient method for maneuver recognition
- A new approach for trajectory prediction mixing
  - CYRA motion model which is very accurate for a short term
  - and a prediction based on MR, more adapted for longer term prediction
- Experimental evaluation on a large real data set

Thank you for your attention

Questions?

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