

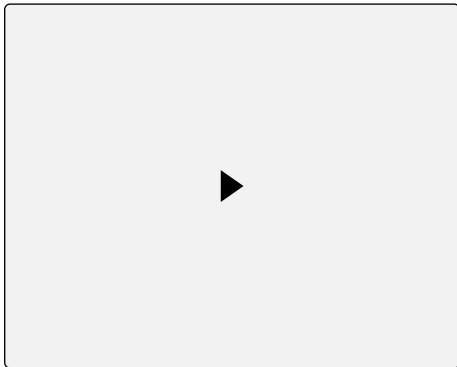
# Realistic Optimization-based Driving Using a Constrained Double-Integrator Model

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# Animation



# Motivation & Problem Statement

Given a 7-tuple  $(\mathcal{X}, \mathcal{U}, x_{\text{initial}}, X_{\text{goal}}, f, J, \{t_i\}_{i=1, \dots, m})$ , the discrete-time optimal trajectory planning problem is defined as:

$$u^* = \arg \min_{u \in \mathcal{U}^{m-1}} \sum_{i=1}^{m-1} J(x_{i+1}, u_i), \quad (1)$$

$$\text{s.t.} \quad x_1 = x_{\text{initial}} \quad (2)$$

$$x_m \in X_{\text{goal}} \subseteq \mathcal{X} \quad (3)$$

$$(x_i, u_i) \in \mathcal{C} \subseteq \mathcal{X} \times \mathcal{U} \quad \text{for all } i \in \{1, \dots, m-1\} \quad (4)$$

$$x_{i+1} = f(x_i, u_i, \Delta t_i) \quad \text{for all } i \in \{1, \dots, m-1\} \quad (5)$$

# Convex vs Non-Convex



# Solver Times

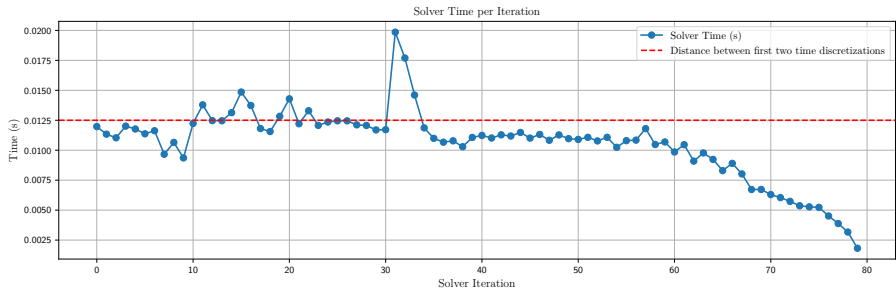


Figure: Convex

# Solver Times

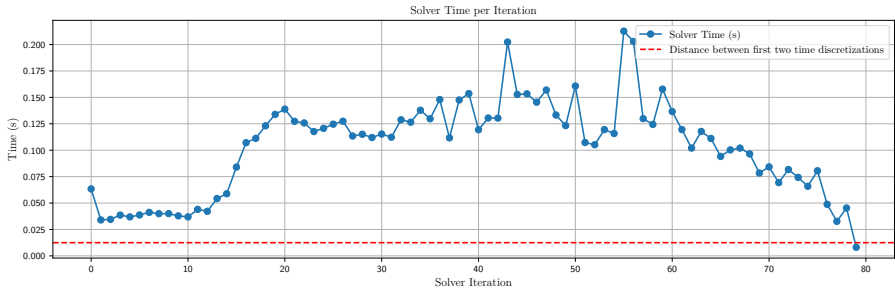
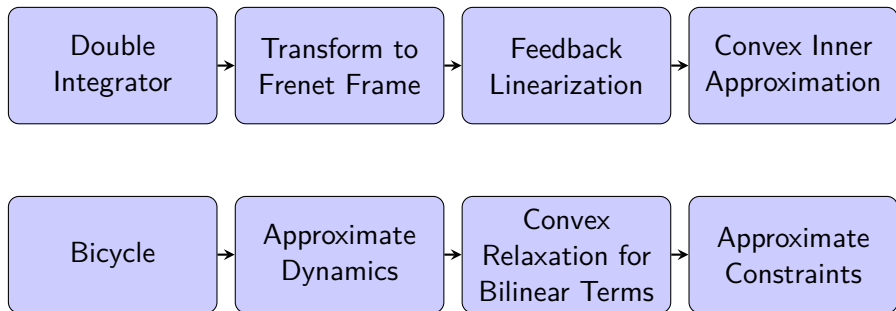


Figure: Non-Convex

# Convex Optimization in Motion Planning

- Non-convex formulations often lack robust convergence criteria.
- Our approach transforms the problem into a convex formulation to ensure:
  - Reliable convergence guarantees.
  - Predictable and efficient computation times.
  - Efficient checkability of the convexity.

# Overview of the Methodology





# Vehicle Modeling: Double Integrator Model (DI)

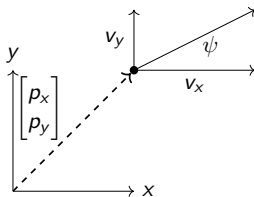


Figure: Double Integrator Model

- Transform to Frenet Frame, introduce Assumption  $\xi = 0$ .
- Feedback Linearization.
- Convex Inner Approximation.

# Coordinate Transformation: Frenet Frame

- Transforms global coordinates into a path-following system.
- Simplifies handling of road curvature and lateral deviations.
- This transformation introduces nonlinear vehicle dynamics.

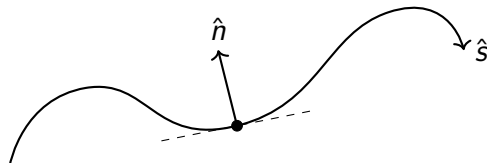


Figure: Frenet Frame Representation

$$\xi = \psi - \theta, \text{ where } \theta \text{ is the angle of the reference path.} \quad (6)$$

$$C(s) = \frac{d\theta}{ds} \quad (7)$$

## Resulting Model &amp; Simplifications

$$x_{di} = \begin{bmatrix} s & n & \xi & \dot{s} & \dot{n} & \dot{\psi} \end{bmatrix}^T \quad (8)$$

$$u_{di} = \begin{bmatrix} a_x & a_y & a_\psi \end{bmatrix}^T \quad (9)$$

$$\overbrace{\begin{bmatrix} \dot{s} \\ \dot{n} \\ \dot{\psi} - C(s)\dot{s} \\ \frac{a_{x,tn} + 2\dot{n}C(s)\dot{s} + nC'(s)\dot{s}^2}{1 - nC(s)} \\ a_{y,tn} - C(s)\dot{s}^2(1 - nC(s)) \\ a_\psi \end{bmatrix}}^{\dot{x}_{di} =} \quad \xRightarrow{\xi = 0} \quad \begin{bmatrix} \dot{s} \\ \dot{n} \\ 0 \\ \frac{a_x + 2\dot{n}C(s)\dot{s} + nC'(s)\dot{s}^2}{1 - nC(s)} \\ a_y - C(s)\dot{s}^2(1 - nC(s)) \\ \ddot{\theta} \end{bmatrix}$$

# Feedback Linearization Technique

- Linearize the vehicle's nonlinear dynamics.

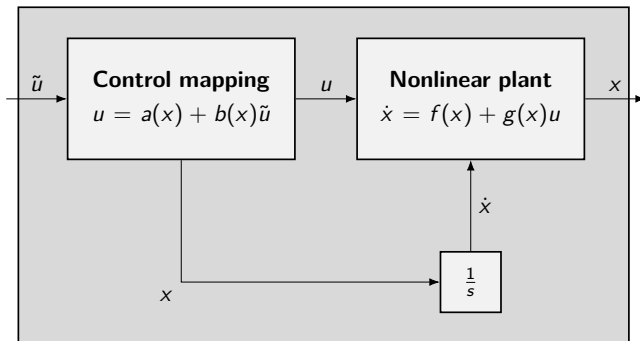


Figure: Feedback control structure for a nonlinear system.

# Resulting Model

$$\tilde{x}_{di} = \begin{bmatrix} s, & n, & \dot{s}, & \dot{n} \end{bmatrix}^T \quad (10)$$

$$\tilde{u}_{di} := \begin{bmatrix} u_t & u_n \end{bmatrix}^T \quad (11)$$

$$\frac{d\tilde{x}_{di}}{dt} = \begin{bmatrix} \dot{s} \\ \dot{n} \\ u_t \\ u_n \end{bmatrix} \quad (12)$$

# Constraint Handling in the Framework

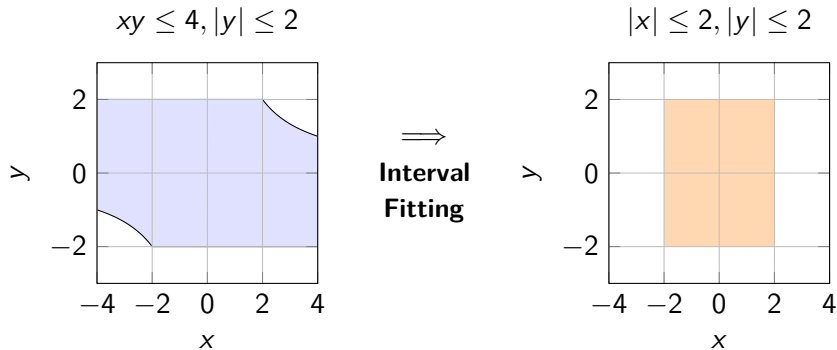
- Feedback linearization leads to nonlinear physical constraints: acceleration, velocity, and road boundaries.
- Using convex inner approximations for non-convex constraints.

$$\hat{\mathcal{C}} = \left\{ \begin{bmatrix} \tilde{x}_{di} \\ \tilde{u}_{di} \end{bmatrix} \mid N \begin{bmatrix} \tilde{x}_{di} \\ \tilde{u}_{di} \end{bmatrix} \leq b \right\} \subseteq \mathcal{C}, \quad (13)$$

- We apply quantifier elimination, using two approaches:
  - Interval Fitting and
  - Cylindrical Algebraic Decomposition (CAD).

$$\tilde{\mathcal{C}} = \left\{ \begin{bmatrix} \dot{s} \\ u_t \\ u_n \end{bmatrix} \mid \begin{bmatrix} \tilde{x}_{di} \\ \tilde{u}_{di} \end{bmatrix} \in \mathcal{C}, \quad \forall \begin{bmatrix} s \\ n \\ \dot{n} \end{bmatrix} \in \begin{bmatrix} \underline{s}, \overline{s} \\ \underline{n}, \overline{n} \\ \underline{\dot{n}}, \overline{\dot{n}} \end{bmatrix} \right\}. \quad (14)$$

## Interval Fitting Illustration



# Cylindrical Algebraic Decomposition

- It is applied to polynomials and divides the space into cylindrical cells.
- Example for  $x^2 + bx + 1$ .

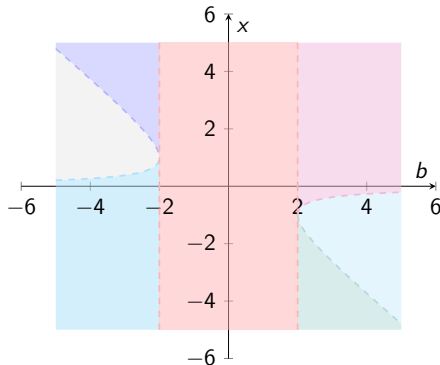
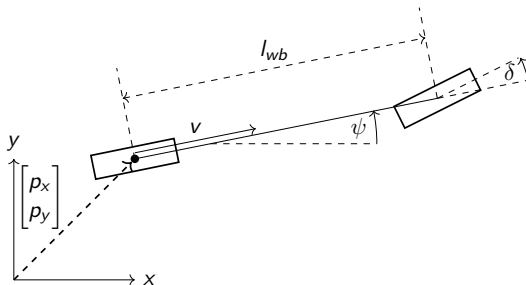


Figure: Illustrating the cells with shaded regions.



# Vehicle Modeling: Kinematic Bicycle Model (KST)



**Figure:** Bicycle model representation of a vehicle.

- Transform to Frenet Frame.
- Approximate Dynamics.
- Convex Relaxation for Bilinear Terms.
- Approximate Constraints.

# KST Dynamics

$$x_{kst} = \begin{bmatrix} s & n & \xi & v & \delta \end{bmatrix}^T \quad (15)$$

$$u_{kst} = \begin{bmatrix} a & v_\delta \end{bmatrix}^T \quad (16)$$

$$\dot{x}_{kst} = \begin{bmatrix} \frac{v \cos \xi}{1 - nC(s)} \\ v \sin \xi \\ \frac{1}{l_{wb}} v \tan \delta - C(s) \dot{s} \\ a \\ v_\delta \end{bmatrix} \quad (17)$$

# Small Angle Approximation

- For small steering angles, trigonometric functions can be approximated.
- This simplifies the nonlinear equations in the bicycle model.

$$\begin{bmatrix} \frac{v \cos \xi}{1 - nC(s)} \\ v \sin \xi \\ \frac{1}{l_{wb}} v \tan \delta - C(s) \dot{s} \\ a \\ v_{\delta} \end{bmatrix} \quad (18)$$

# McCormick Relaxation for Bilinear Terms

- McCormick relaxation provides a convex envelope for bilinear terms such as  $w = v_1 v_2$ .
- Given  $v_1 \in [\underline{v}_1, \overline{v}_1]$  and  $v_2 \in [\underline{v}_2, \overline{v}_2]$ , the McCormick envelopes are:

$$w \geq \underline{v}_1 v_2 + \underline{v}_2 v_1 - \underline{v}_1 \underline{v}_2,$$

$$w \geq \overline{v}_1 v_2 + \overline{v}_2 v_1 - \overline{v}_1 \overline{v}_2,$$

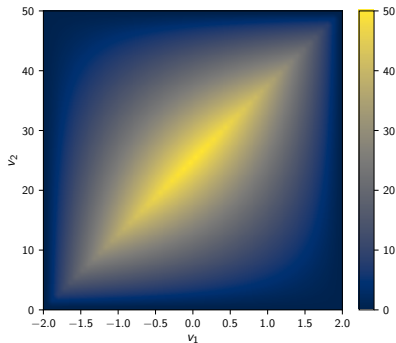
$$w \leq \overline{v}_1 v_2 + \underline{v}_2 v_1 - \overline{v}_1 \underline{v}_2,$$

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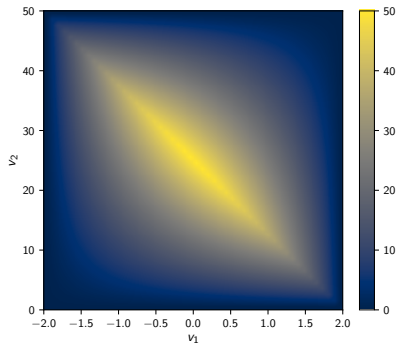
- This relaxation transforms the non-convex bilinear constraint into linear inequalities.

# Example for Different Bounds

●  $-2 \leq v_1 \leq 2$  and  $0 \leq v_2 \leq 50$



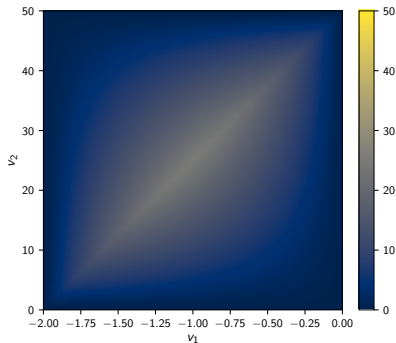
(a) Difference to the upper bound



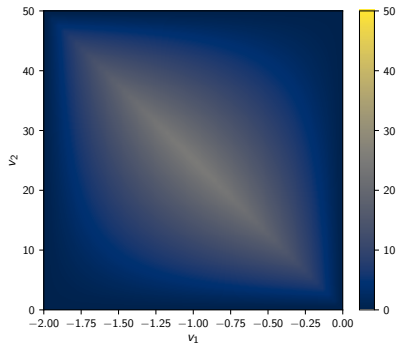
(b) Difference to the lower bound

# Example for Different Bounds

●  $-2 \leq v_1 \leq 0$  and  $0 \leq v_2 \leq 50$



(c) Tighter upper bound on  $w$



(d) Tighter lower bound on  $w$

# Implementation Details and Evaluation Metrics

- We define road segments, planner configurations, and soft constraints.
- Simulation scenarios mimic realistic driving conditions.
- Multiple scenarios: straight roads, curved segments.
- Metrics: trajectory feasibility, computational time, road completion, and objective values.

# Performance: Computational Efficiency

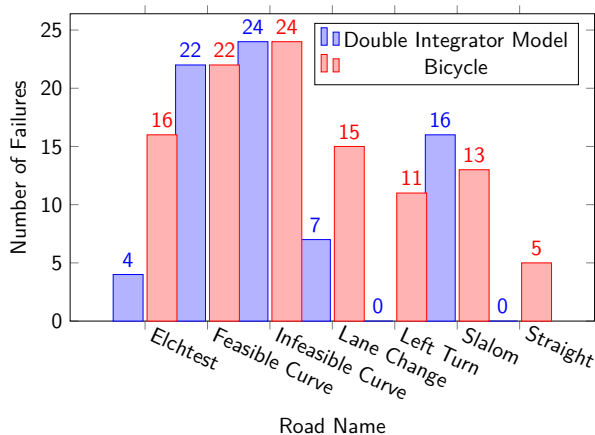
- Solver times validate the framework's efficiency.
- $t_{\text{conf}}^{(1)} = (3\text{s}, 0.1\text{s}, 10\text{ms}, 40\text{ms})$
- $t_{\text{conf}}^{(2)} = (5\text{s}, 0.1\text{s}, 20\text{ms}, 20\text{ms})$

Model	Config	Avg Time	Time Deviation
DI	$t_{\text{conf}}^{(1)}$	3.9ms	1.0ms
DI	$t_{\text{conf}}^{(2)}$	3.8ms	1.3ms
Bicycle	$t_{\text{conf}}^{(1)}$	9.5ms	2.1ms
Bicycle	$t_{\text{conf}}^{(2)}$	9.4ms	2.9ms



# Comparison: Double Integrator vs. Bicycle Model

- Double integrator: Fast and efficient, less detailed.
- Bicycle model: Higher fidelity but increased computational load.
- Trade-offs guide model selection based on application needs.



# Numerical Experiment: Lane Change

- Scenario: Handling a sharp curve.
- Result: Both models perform well on moderate and slower velocities.
- Difference: DI accounts for lateral acceleration from the initial point onward.



# Numerical Experiment: Slalom

- Scenario: Handling a sharp curve.
- Result: KST performs better.
- Inscribed polytope too conservative.



# Numerical Experiment: Left Curve

- Scenario: Minimize control derivatives.
- Result: Approximation errors noticeable for KST.



# Limitations and Challenges

- Conservative approximations can limit feasibility.
- KST performs worse in high speed scenarios, due to restricted friction circle.

$$\sqrt{a^2 + (v\dot{\psi})^2} = \sqrt{a^2 + \left(\frac{v^2}{l_{wb}} \tan(\delta)\right)^2} \leq a_{max} \quad (19)$$

# Summary

- Proposed a convex optimization framework for motion planning.
- Demonstrated realistic, safe trajectories with a constrained double-integrator and kinematic bicycle model.
- Validated through extensive simulations and performance evaluations.

# Future Work

- Continue work on the KST model.
- Open work on the inscribed polytope, i.e. restrict  $n \in [0, \bar{n}]$  in right curves.
- Implement the problem without the need of constraints compilation during runtime.

# Animation

