SIMS 2015 Plenary

Accomplishing Ground Moving Innovations through Modeling, Simulation, and Optimal Control

Lars Eriksson

lars.eriksson@liu.se

Professor

Division of Vehicular Systems

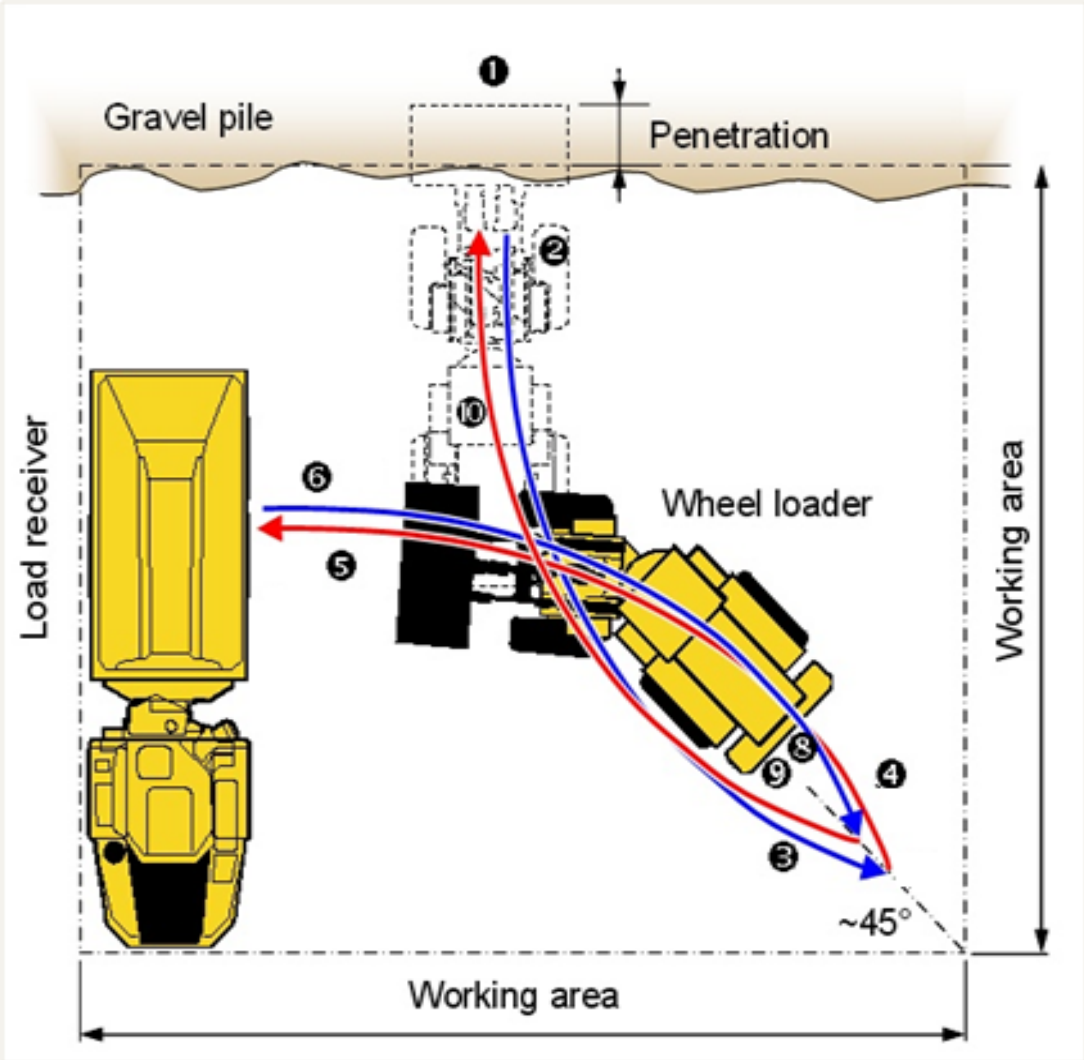
Department of Electrical Engineering

Linköping University

The Application

Big Toys for Big Boys

The Application
Short Loading Cycle



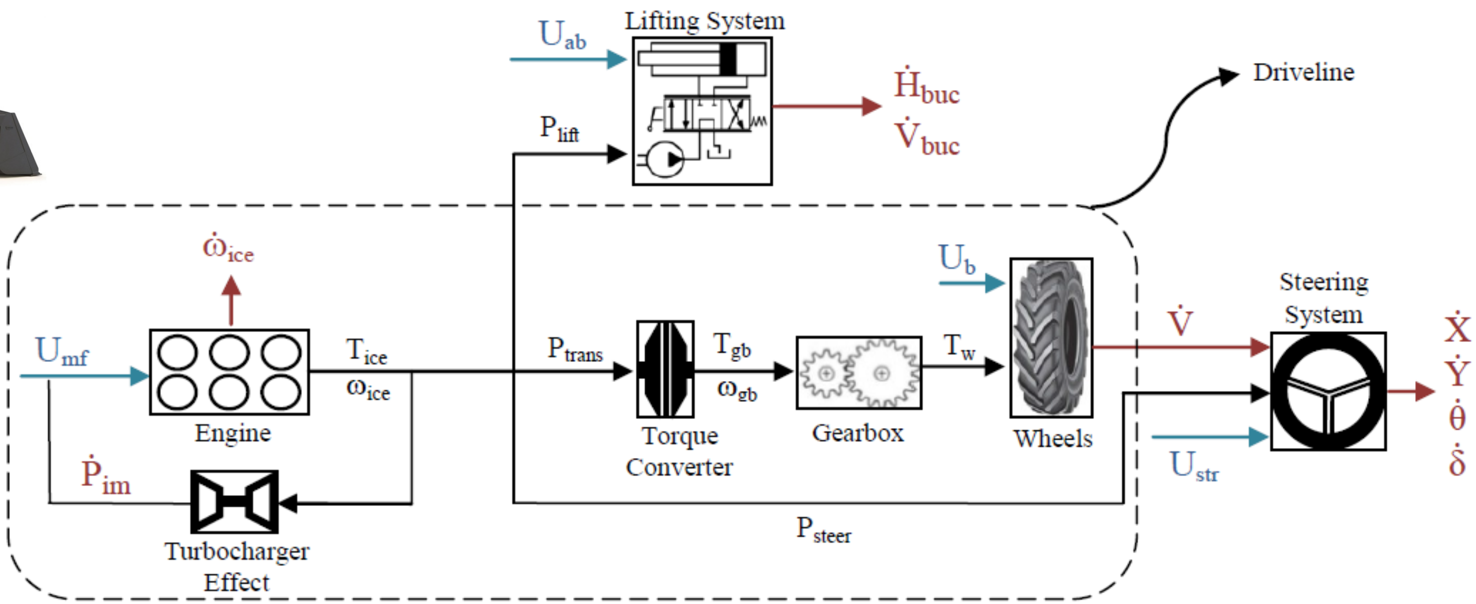
- Pick up gravel
- Reverse and lift
- Stop
- Drive and lift
- Empty bucket
- Reverse and lower
- Stop
- Drive
- Fill Bucket

-How to drive optimally?

Outline

- Wheel loader application
  - How to operate the wheel loader optimally
  - Modeling for control and optimal control
- Formulating and solving the optimal control problem
  - Numerical optimal control
- Design problems and trade-offs
  - Solving fuel and time optimal driving
  - Design case – Stiff converter
  - Design case – Intelligent braking
  - Design case – Where to park load receiver?
- Conclusions

Wheel loader model



Sub systems :

1- Driveline

Controls: *Fuel injection, Brake torque signal.*

States: *Engine speed, Intake manifold pressure, Vehicle speed.*

2- Lifting system

Controls: *Bucket lift acceleration.*

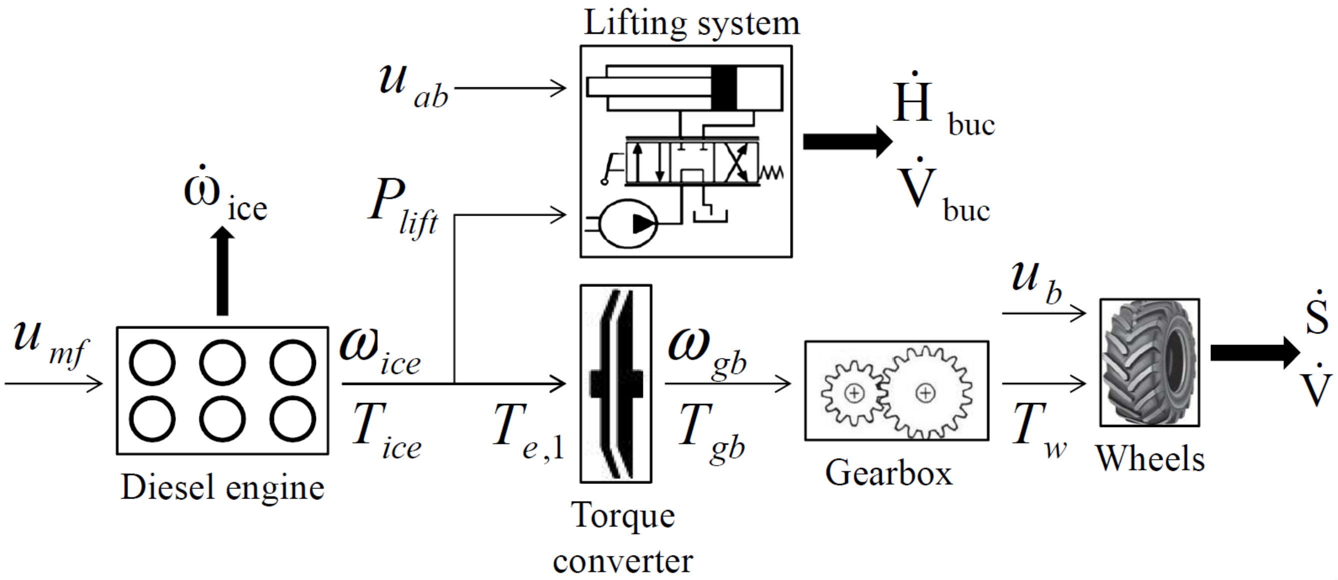
States: *Bucket height, Bucket lift speed.*

3- Steering system

Controls: *Derivative of steering angle.*

States: *Vehicle position X & Y, Heading angle, Steering angle.*

Wheel loader model



$$\text{States}: \begin{Bmatrix} \omega_{ice} \\ S \\ V \\ H_{bucket} \\ V_{bucket} \end{Bmatrix} = \begin{Bmatrix} Engine\ \ speed \\ Travelled\ \ distance \\ Vehicle\ \ speed \\ Lift\ \ height \\ Lift\ \ speed \end{Bmatrix}$$

$$\text{Controls}: \begin{Bmatrix} U_{mf} \\ U_{ab} \\ U_b \end{Bmatrix} = \begin{Bmatrix} Fuel \\ Bucket\ \ acceleration \\ Braking\ \ torque \end{Bmatrix}$$

$$\frac{d\omega_{ice}}{dt} = \frac{1}{J_{ice}}\left(T_{ice}(U_{mf}, \omega_{ice}) - \frac{P_{load}(V_{buc}, V)}{\omega_{ice}}\right) \quad (1)$$

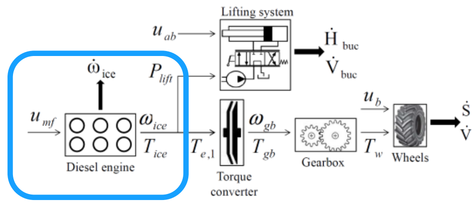
$$\frac{dS}{dt} = V \quad (2)$$

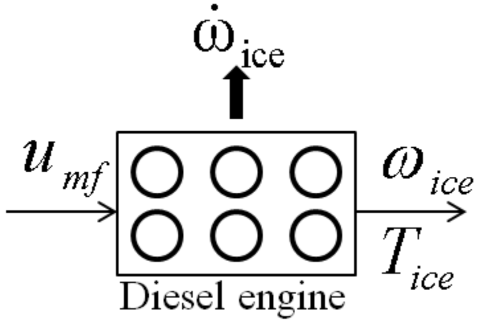
$$\frac{dV}{dt} = \frac{sign(\gamma)\left(F_{trac}(U_b, \omega_{ice}) - F_{roll}\right)}{M_{tot}} \quad (3)$$

$$\frac{dH_{buc}}{dt} = V_{buc} \quad (4)$$

$$\frac{dV_{buc}}{dt} = U_{ab} \quad (5)$$

Diesel engine model





$$T_{ice} = T_{ig} - T_{fric}$$

$$\eta_{ig} = \eta_{ig,ch}\left(1 - \frac{1}{r_c^{\gamma_{cyl}-1}}\right)$$

$$T_{ig} = \frac{\eta_{ig}\, q_{hv}\, n_{cyl}\, U_{mf}\, 10^{-6}}{2\,\pi\, n_r}$$

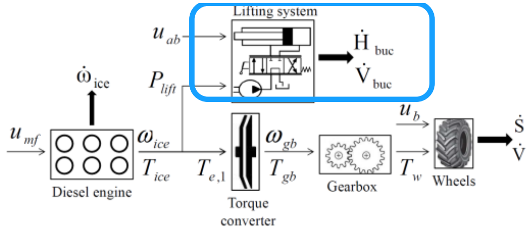
$$T_{fric} = \frac{V_d\, 10^5}{4\pi}\left(c_{fr1}\,\omega_{ice}{}^2 + c_{fr2}\,\omega_{ice} + c_{fr3}\right)$$

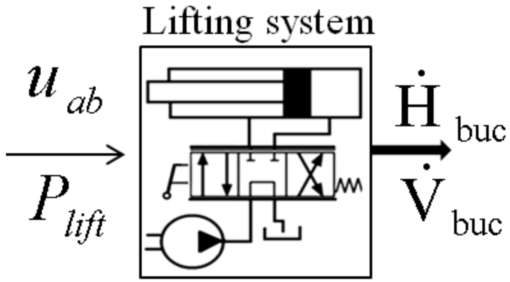
$$\dot{m}_f = \frac{10^{-6}}{4\,\pi} U_{mf}\,\omega_{ice}\, n_{cyl}$$

$$P_{load} = P_{trac} + P_{lift}$$

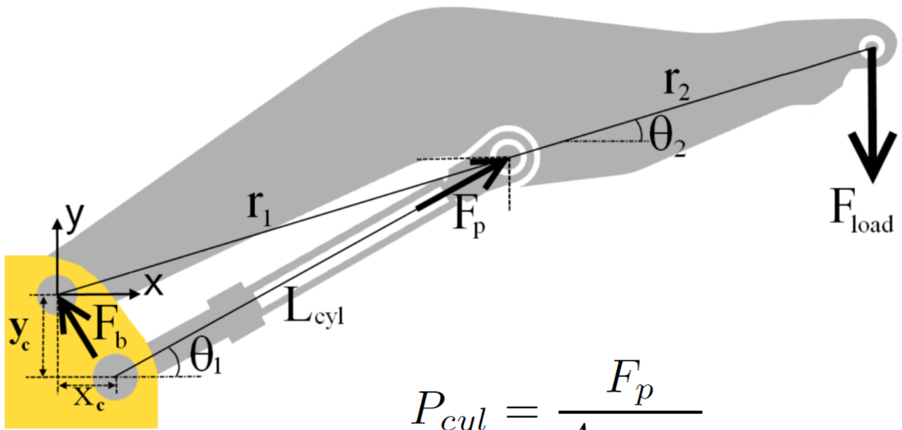
$$\frac{d\omega_{ice}}{dt} = \frac{1}{J_{ice}}\left(T_{ice}(U_{mf}, \omega_{ice}) - \frac{P_{load}(V_{buc}, V)}{\omega_{ice}}\right) \qquad (1)$$

Lift system and constraints

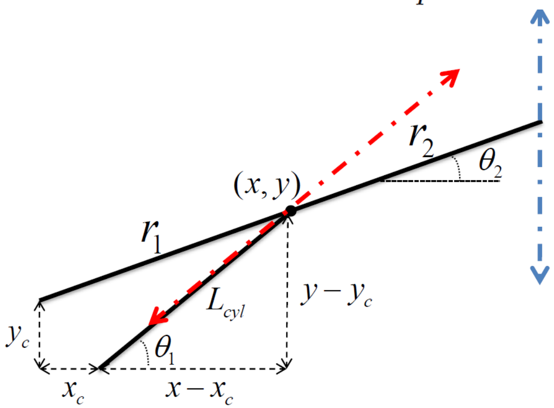




$$F_{load} = M_{buc}\,(g + U_{ab})$$
$$P_{lift,net} = F_{load}\,V_{buc}$$
$$P_{lift} = \frac{(1 + C_{loss})\,P_{lift,net}}{\eta_{lift}}$$



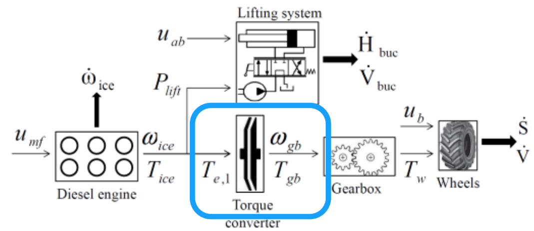
$$P_{cyl} = \frac{F_p}{A_{piston}}$$

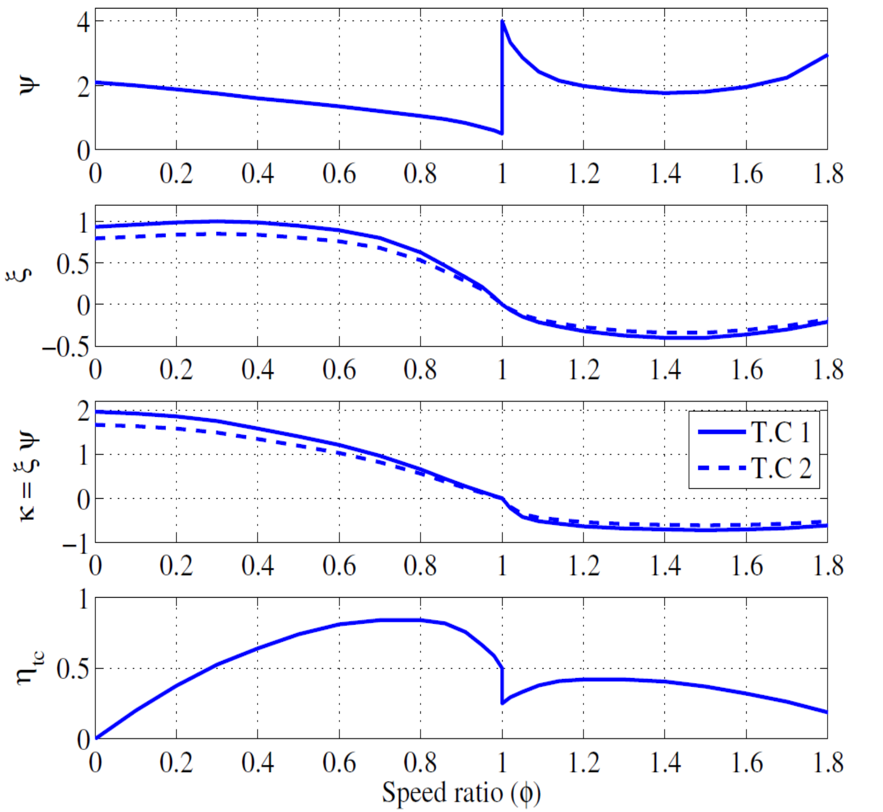


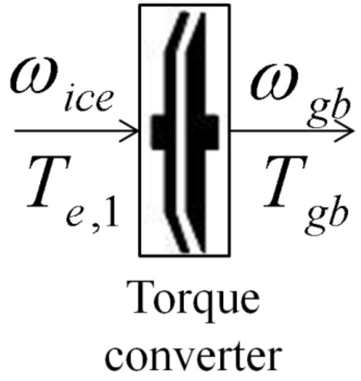
$$\frac{dH_{buc}}{dt} = V_{buc} \qquad (4)$$
$$\frac{dV_{buc}}{dt} = U_{ab} \qquad (5)$$

$$V_{lift,max} = k(\theta_2)\,v_{pist,max}$$

Torque converter







$$\phi = \frac{|\text{gearbox speed}|}{\omega_{ice}}$$

$$\eta_{tc} = \begin{cases} \phi \cdot \psi & \phi \leq 1 \\ \dfrac{1}{\phi \cdot \psi} & \phi \succ 1 \end{cases}$$

$$\kappa(\phi) = \psi(\phi)\,\xi(\phi)$$

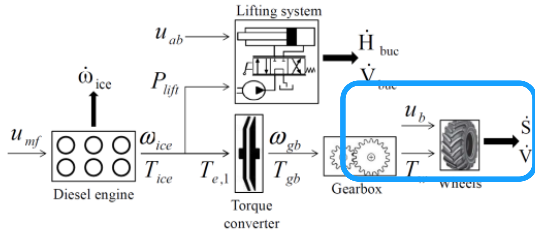
$$T_{e,1} = \xi(\phi)\,(\frac{\omega_{ice}}{1000})^2$$

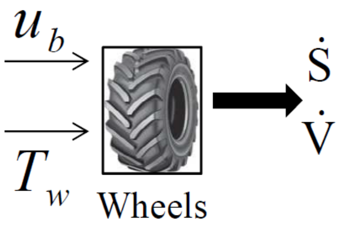
$$T_{gb} = \kappa(\phi)\,(\frac{\omega_{ice}}{1000})^2 \;|\,sign(\gamma)\,|$$

$$P_{trac} = T_{e,1}\,\omega_{ice}$$

- *2 T.C. studied (one delivers 15 % more torque)*
- *Remove the discontinuities (efficient numerical optimization)*
  - *Differentiable model*

Vehicle speed and position



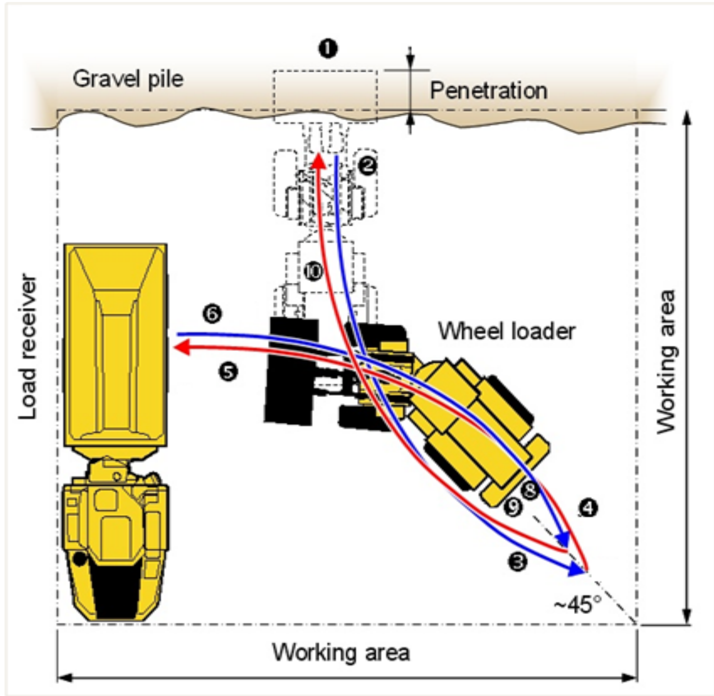


$$F_{trac} = \frac{T_w - sign(V)\, T_b}{r_w}$$

$$F_{roll} = c_r\, (M_{veh} + M_{buc})\, g$$

$$T_w = T_{gb}\, \eta_{gb}\, \gamma$$

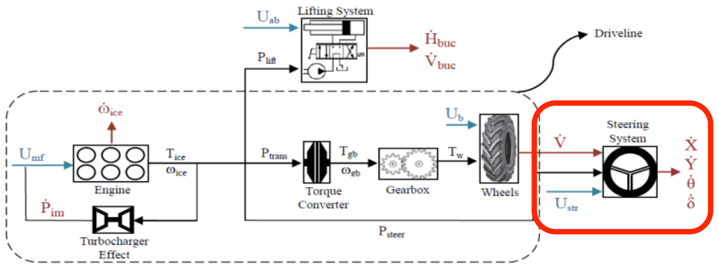
$$T_b = U_b$$



$$\frac{dS}{dt} = V \tag{2}$$

$$\frac{dV}{dt} = \frac{sign(\gamma)\Big(F_{trac}(U_b, \omega_{ice}) - F_{roll}\Big)}{M_{tot}} \tag{3}$$

Steering system and vehicle position



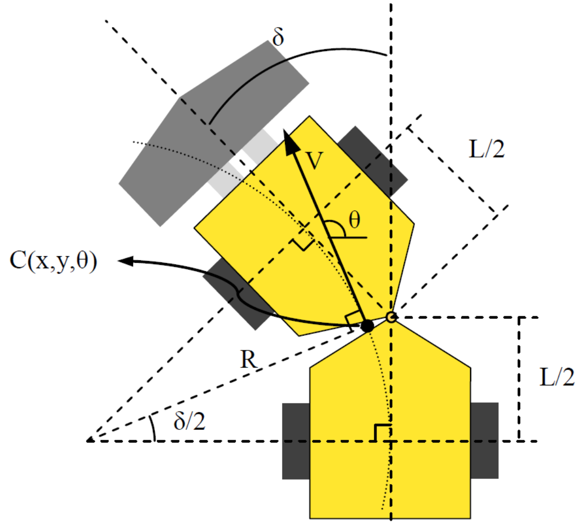
$$P_{steer} \propto \text{Derivative of steering angle } U_{str}^{2}$$

$$\frac{d\delta}{dt} = U_{str}$$

$$\frac{d\theta}{dt} = \frac{V}{R}$$

$$\frac{dX}{dt} = V\cos(\theta)$$

$$\frac{dY}{dt} = V\sin(\theta)$$



Constraints during steering

Continuous steering angle

$$U_{str,min} \leq U_{str} \leq U_{str,max}$$

Minimum turning radius

$$R_{min} \leq \frac{L}{2\tan(\frac{\delta}{2})} = R$$

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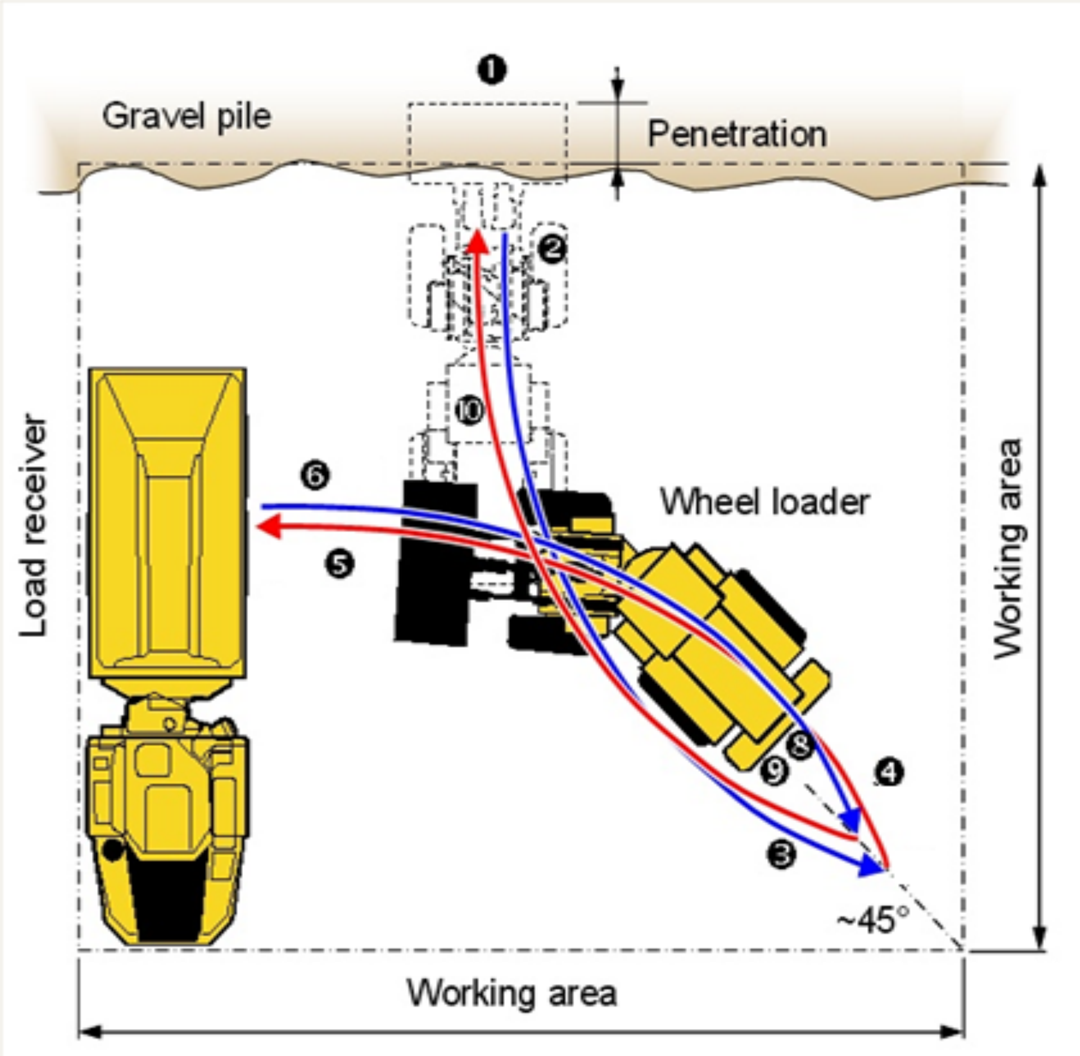
How to drive optimally?



Lift transport section (and complete cycle)

- Minimum Time
- Minimum Fuel

Optimal Control Problem
Complete cycle – Fork lift application

$$\min_{s(t),u(t),\gamma(t)} \quad T \quad \text{or} \quad M_f$$

s.t.

$$\begin{aligned}
\dot{s}(t) &= f(s(t), u(t), \gamma(t)) \\
u_{min} \leq u(t) &\leq u_{max} \\
s_{min} \leq s(t) &\leq s_{max} \\
R &\leq R_{max} \\
T_{ice}(s(t), u(t)) &\leq T_{ice,max} \\
p_{cyl}(s(t), u(t)) &\leq p_{cyl,max} \\
s(0) &= \left(120, 0, 0, 0, 1.1 \times 101300, \frac{\pi}{2}, 0, 0, 0\right) \\
t \in [0, t_1] : \ \gamma(t) &= 0, h_{lift}(t_1) = 0.2, \\
t \in [t_1, t_2] : \ \gamma(t) &= -60, \\
t \in [t_2, t_3] : \ \gamma(t) &= 0, v(t_3) = 0, \dot{v}_{min} \leq |\dot{v}(t)|, \\
t \in [t_3, t_4] : \ \gamma(t) &= 60, h_{lift}(t_4) = h_{end}, \\
t \in [t_4, t_5] : \ \gamma(t) &= 0, u_{dstr}(t) = u_{ab}(t) = \delta(t) = v(t_5) = 0, \\
\int_{t_4}^{t_5} v \, \mathrm{dt} &= L_p, (x, y)(t_5) = [x_e, y_e], \dot{v}_{min} \leq |\dot{v}(t)|, \\
t \in [t_5, t_6] : \ \gamma(t) &= v(t) = 0, h(t_6) = h_{end} - 0.2, \\
t \in [t_6, t_7] : \ \gamma(t) &= -60, u_{ab}(t) = u_{dstr}(t) = \delta(t) = 0, \\
\int_{t_6}^{t_7} v \, \mathrm{dt} &= -L_p, \\
t \in [t_7, t_8] : \ \gamma(t) &= -60, h_{lift}(t_8) = 0.2, \\
t \in [t_8, t_9] : \ \gamma(t) &= 0, u_{ab}(t) = v(t_9) = 0, \dot{v}_{min} \leq |\dot{v}(t)|, \\
t \in [t_9, t_{10}] : \ \gamma(t) &= 60, u_{ab}(t) = 0, \\
t \in [t_{10}, T] : \ \gamma(t) &= 0, u_{ab}(T) = u_{dstr}(T) = u_b(T) = 0, \\
s(T) &= \left(\text{-}, 0, 0, 0, \text{-}, \frac{\pi}{2}, 0, 0, 0\right), \dot{v}_{min} \leq |\dot{v}(t)|,
\end{aligned}$$

PROPT tool and model implementation

Path to Efficient Solution

- Discretize state and controls in time
  Very large but sparse optimization problems
- Efficient solvers available
  IPOPT, SNOPT, KNITRO
- Efficient by using gradients and hessians.
  Use Algorithmic Differentiation
- Packages enable us to formulate problem and enter models that are differentiable.
  DIRCOL, ACADO, PROPT, CasADi, OpenModelica…
- Can now solve large non-linear problems efficiently

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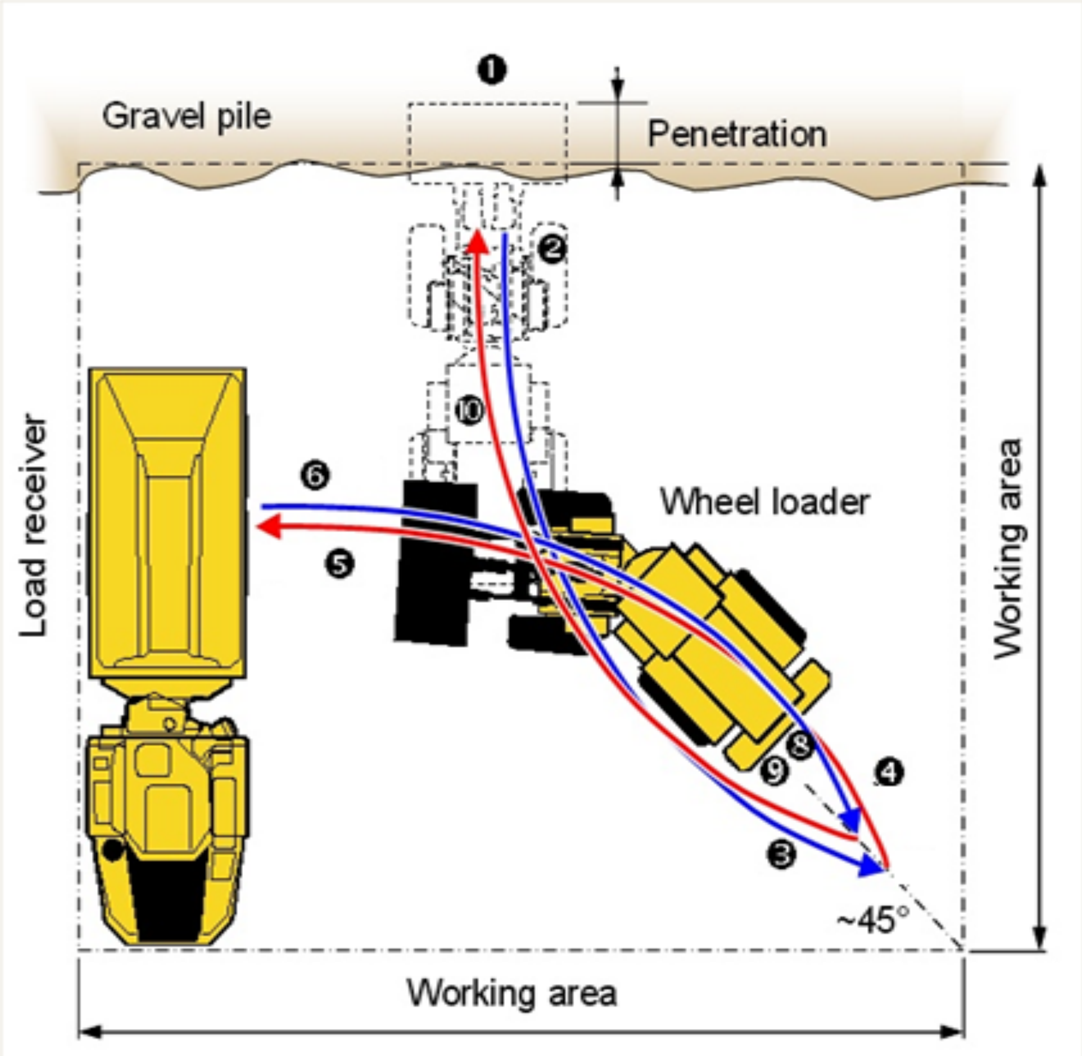
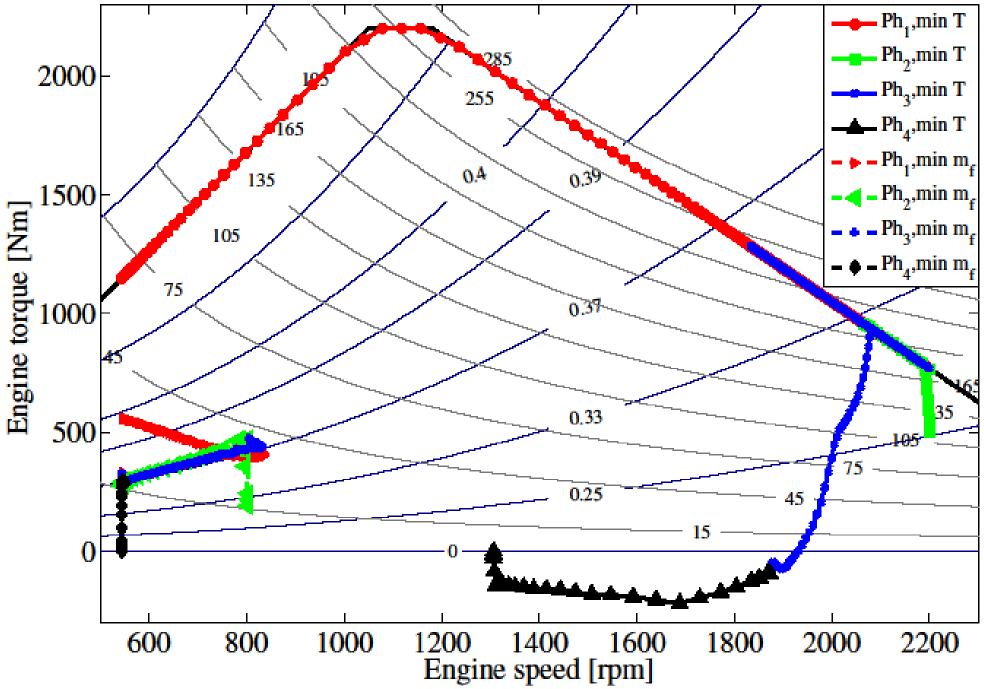
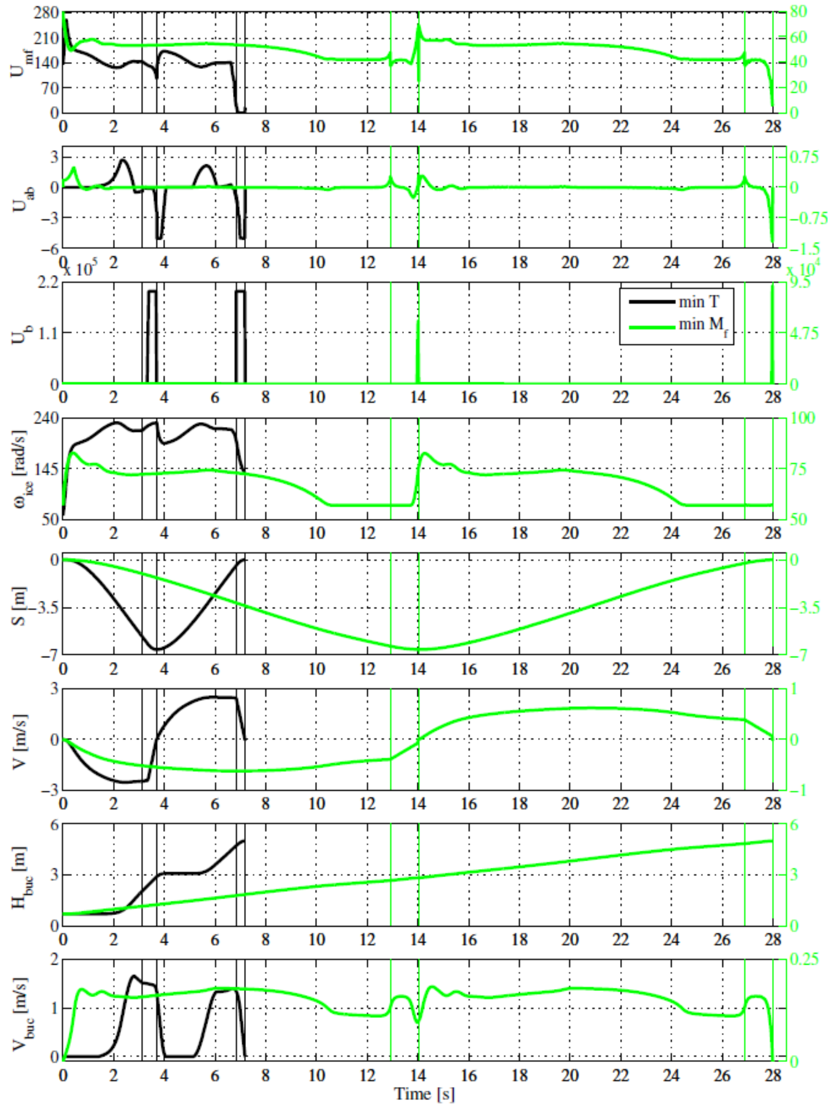


Lift & transport section

- Minimum Time
- Minimum Fuel

Time and fuel optimal solutions, trajectories





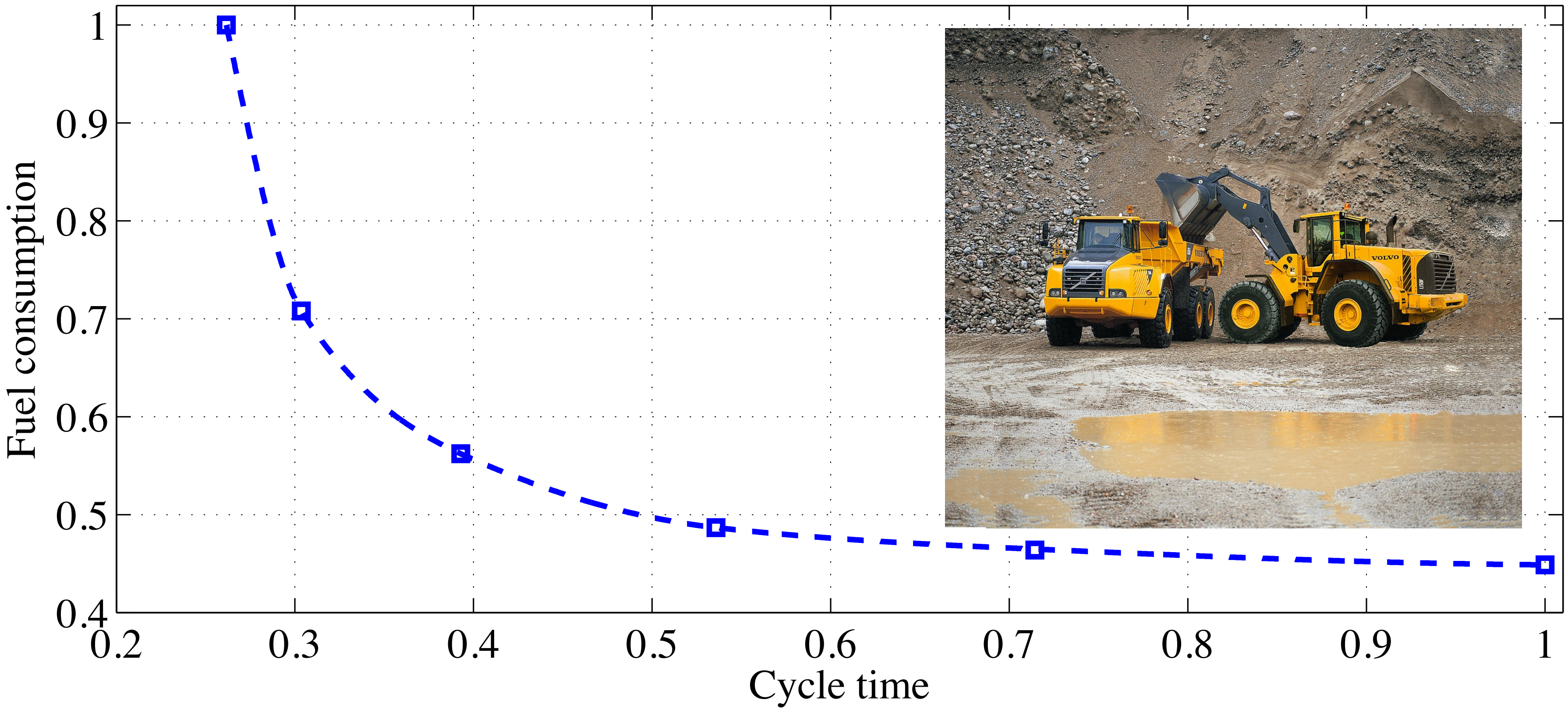
Min T :

acceleration » lifting » acceleration » lifting

Min Fuel:

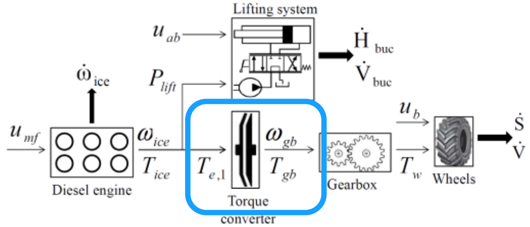
- *Avoiding high engine speeds.*
- *Simultaneous acceleration and lifting*

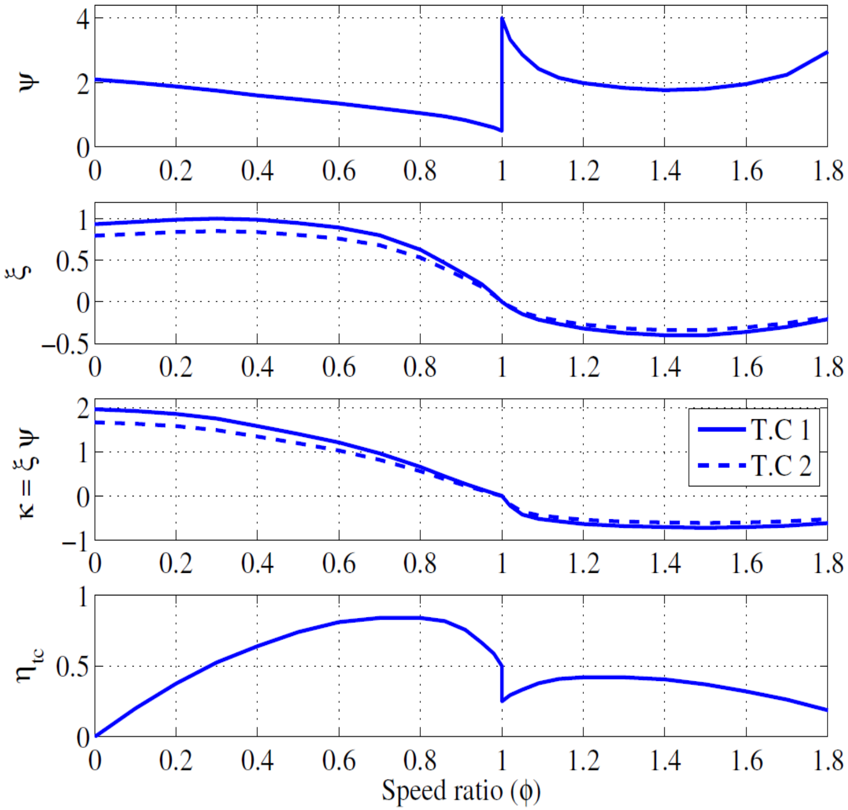
Trade-off between fuel and time optimal

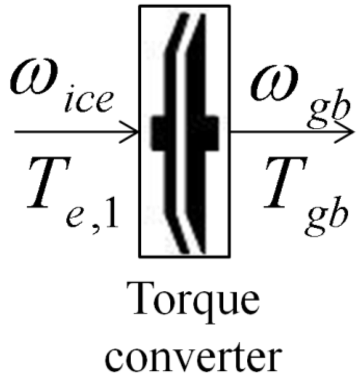


- Pareto front informative
  - Fuel optimal cycle 50 % shorter -> only 5 % fuel cost
  - Time optimal cycle 5 % longer -> 30 % fuel savings
- Total Cost Optimization
  - Site optimization

Torque converter selection







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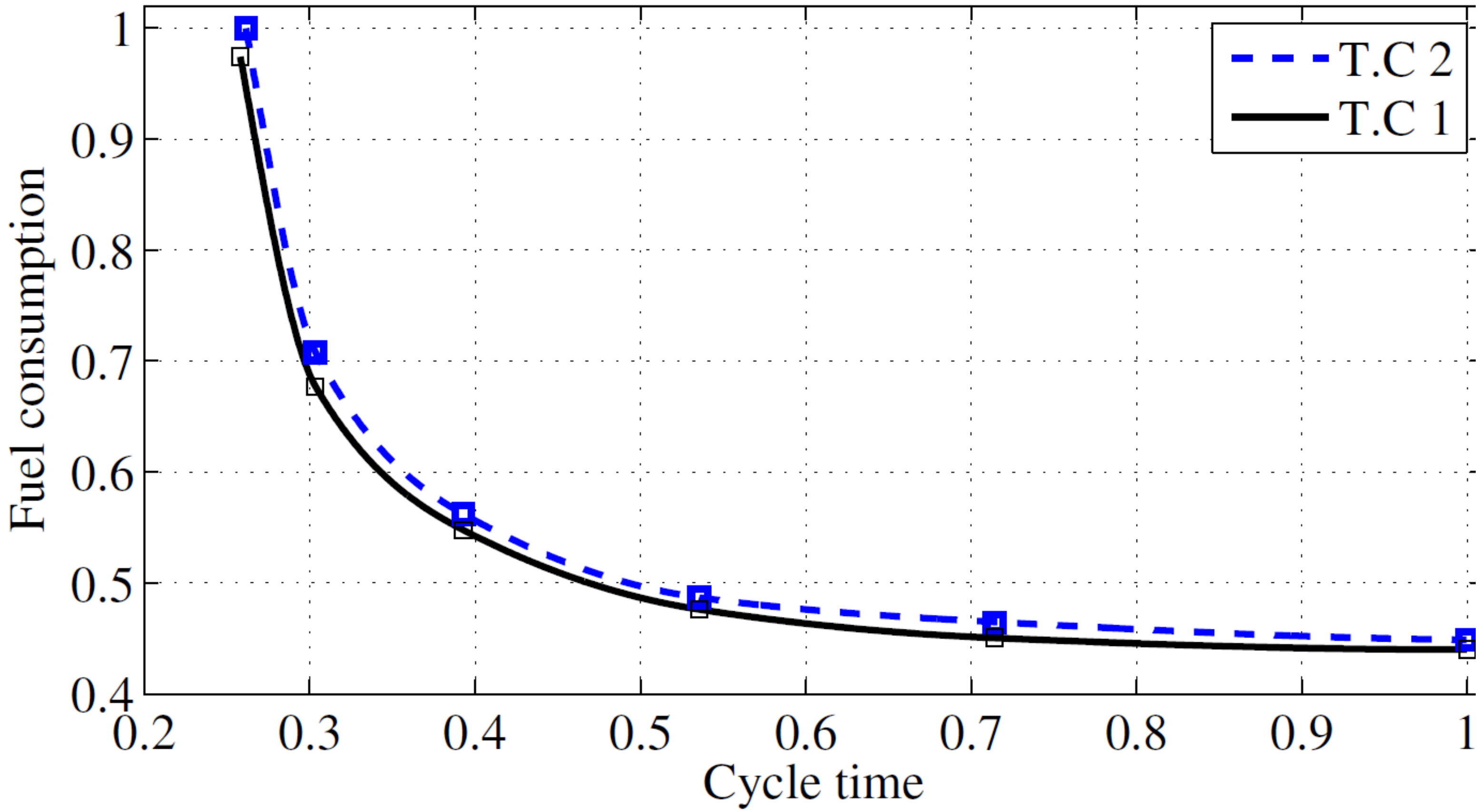
$$T_{e,1} = \xi(\phi)\,(\frac{\omega_{ice}}{1000})^2$$

$$T_{gb} = \kappa(\phi)\,(\frac{\omega_{ice}}{1000})^2 \;|\; sign(\gamma) \;|$$

$$P_{trac} = T_{e,1}\,\omega_{ice}$$

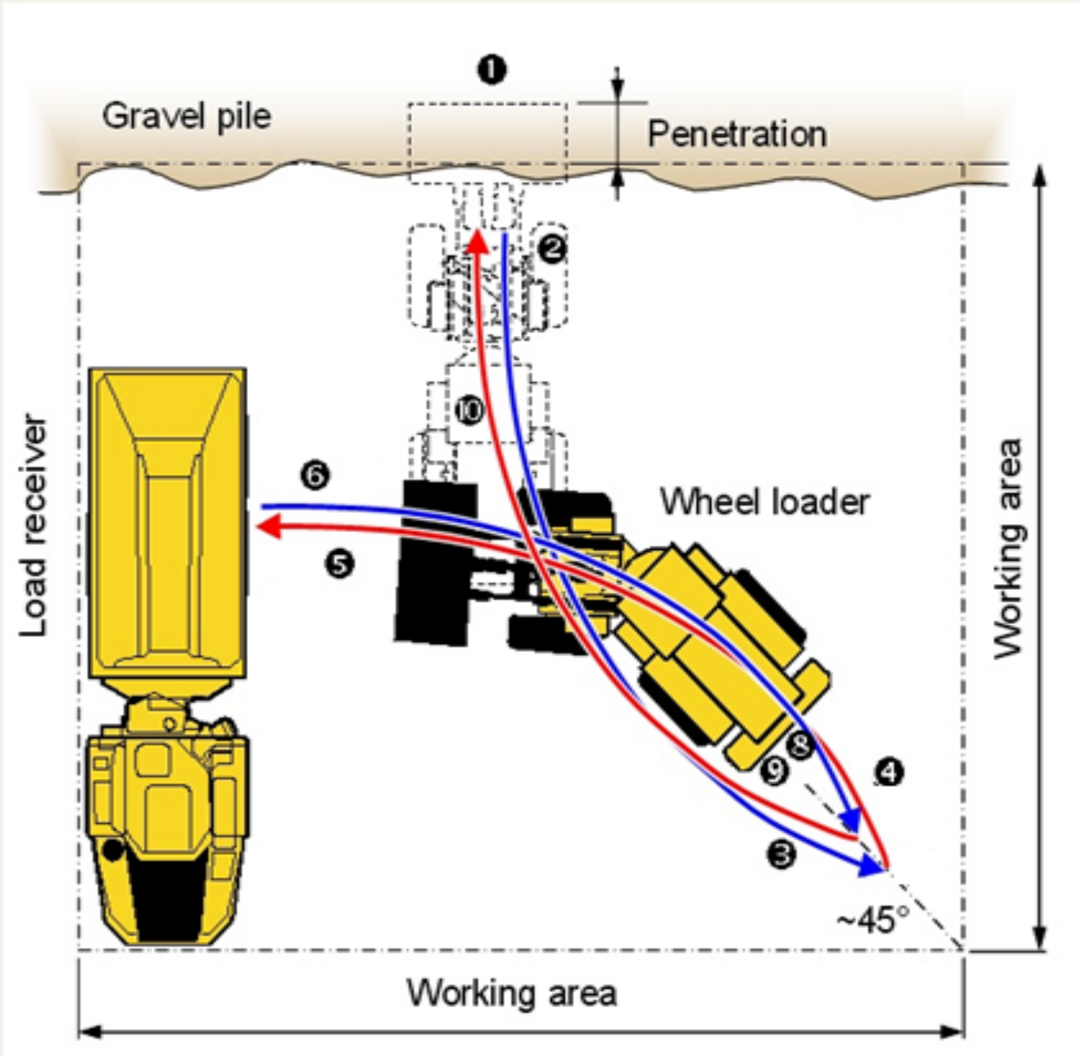
- *2 T.C. studied (one delivers 15 % more torque)*
- *No efficiency difference.*

Trade-off between fuel and time optimal



- Stiff torque converter is proven better – New knowledge
- Its a free lunch.
- In production = Innovation

Intelligent Braking
Torque Converter vs Service Brakes



Easy driving

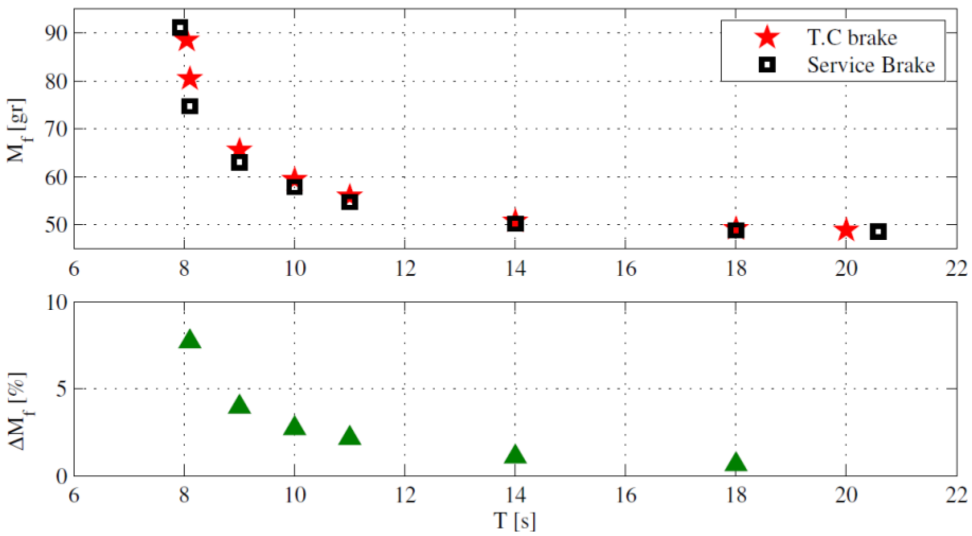
- Switch to reverse
- Use engine and torque converter to brake

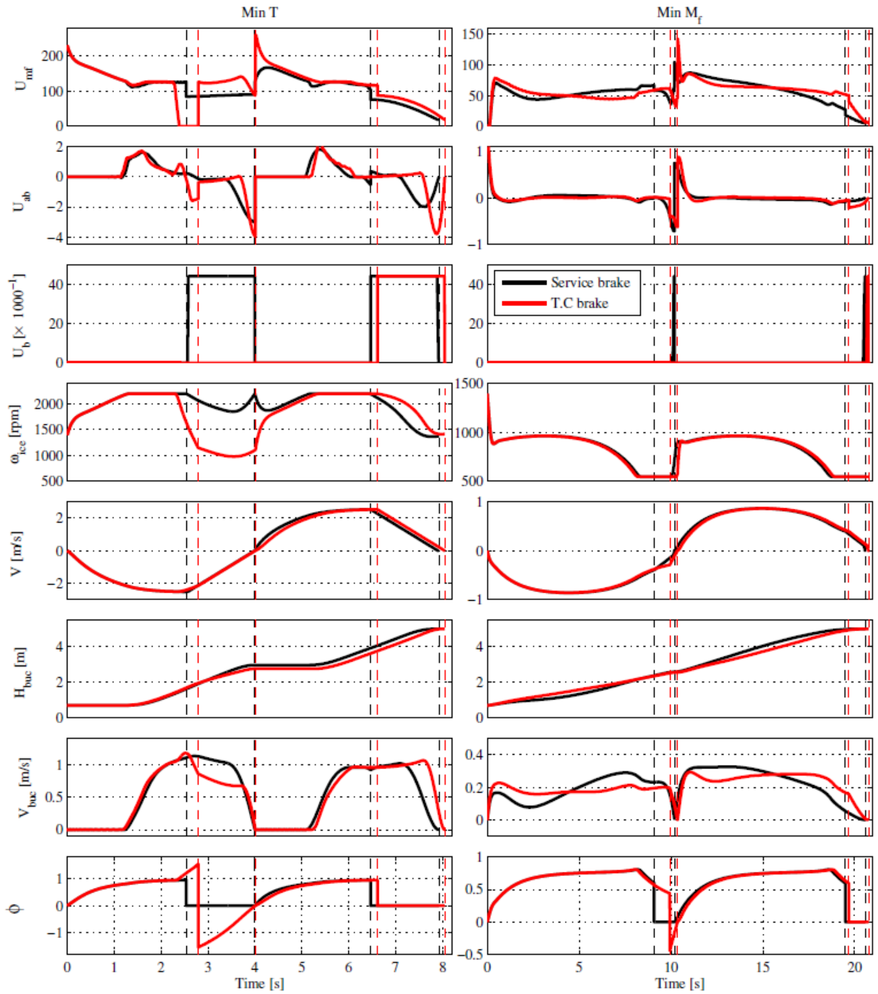
New idéa:

- Switch to reverse
- Control service brakes

- How much is saved?

Intelligent Braking
Torque Converter vs Service Brakes





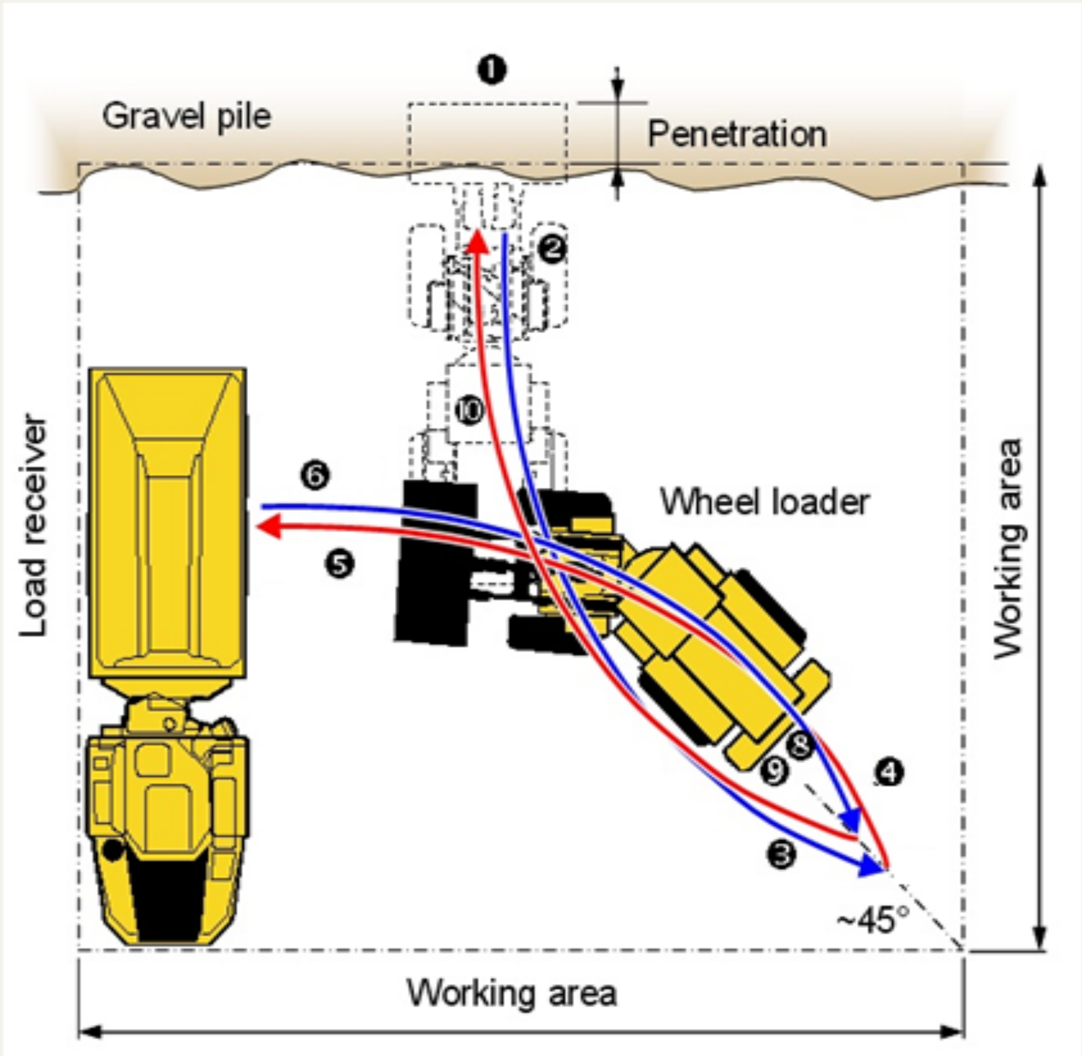
Intelligent braking is

- More efficient
- Faster
- In production = Innovation

LiU EXPANDING REALITY

Optimal Control of Wheel Loader Operation in the Short Loading Cycle Using Two Braking Alternatives.
Vaheed Nezhadali, and Lars Eriksson. In: IEEE VPPC 2013 - The 9th IEEE Vehicle Power and Propulsion Conference. Beijing, China.

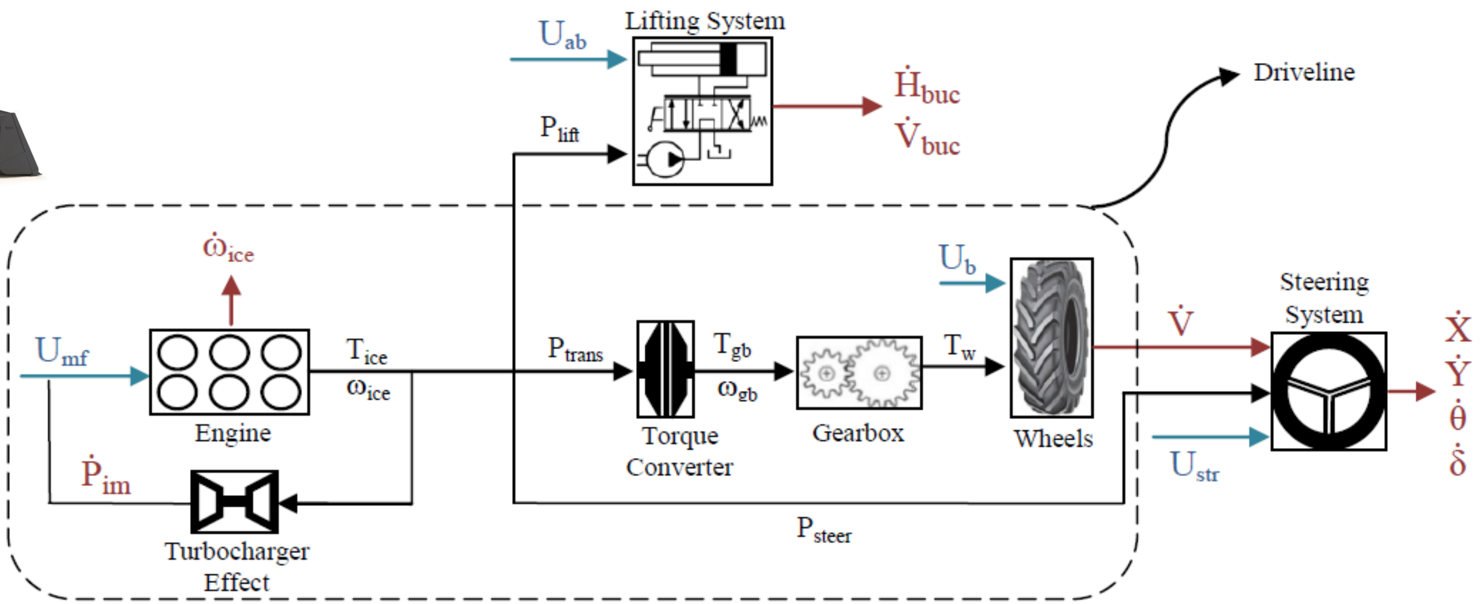
Free Load Receiver Placement



Increased freedom

- Position
- Orientation

Full Wheel Loader Model



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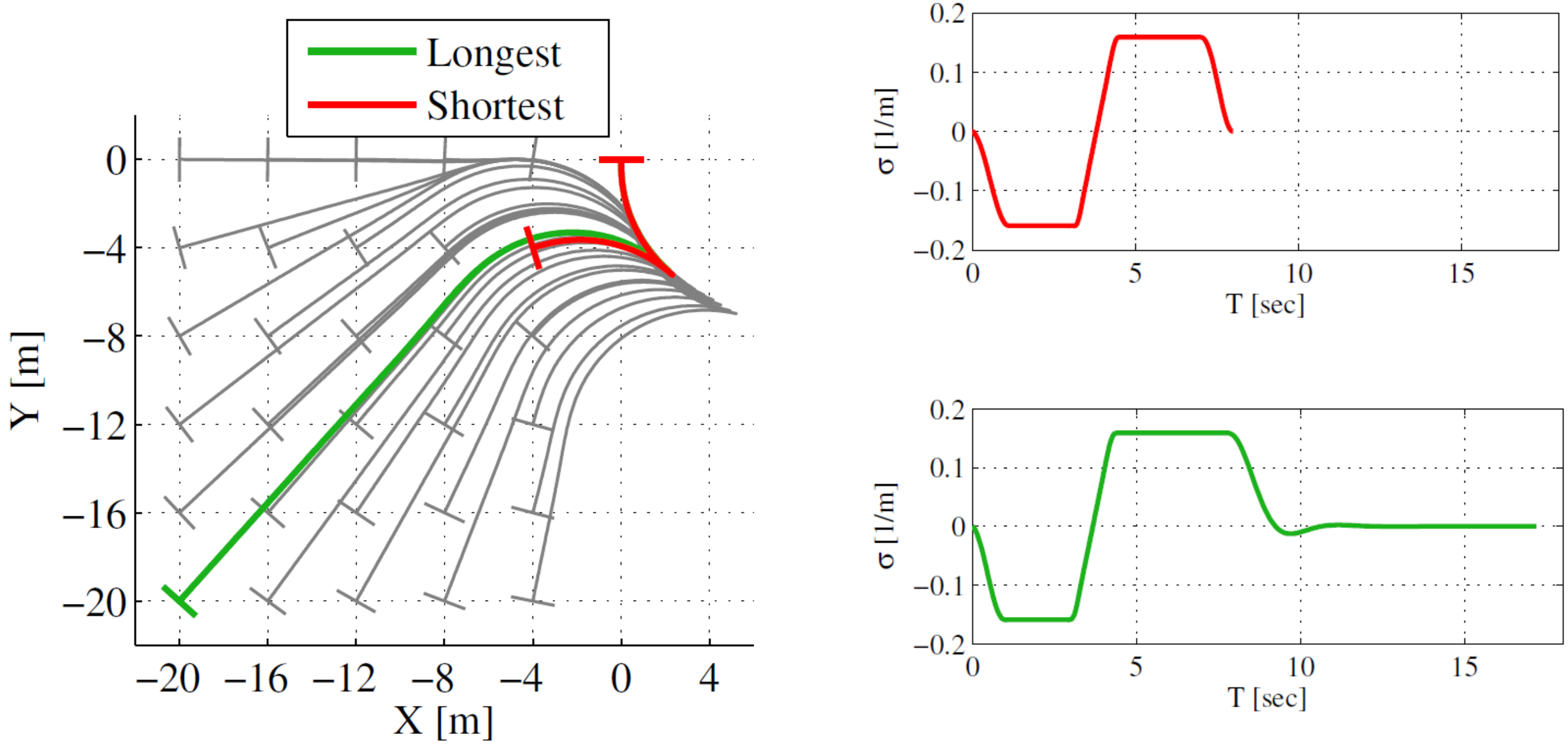
Controls: *Derivative of steering angle.*

States*: Vehicle position X & Y , Heading angle, Steering angle.*

Trajectory from loading point to load receiver
(Half short loading cycle)

Same trajectory for Min M_f and Min T cycles



Optimal lifting and Path Profiles for a Wheel Loader Considering Engine and Turbo Limitations.

Vaheed Nezhadali, and Lars Eriksson.

In: Optimization and Optimal Control in Automotive Systems, In Lecture Notes in Control Sciences, Editors: L. del Re, I. Kolmanovsky, M. Steinbuch and H. Waschl. Springer.

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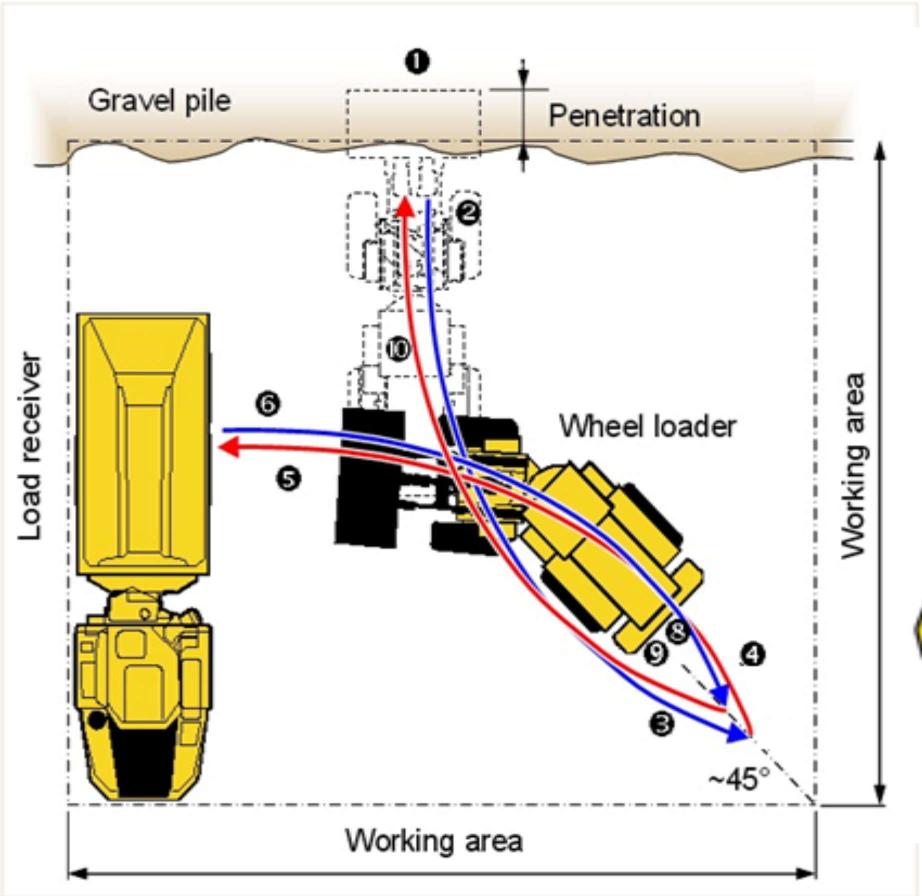
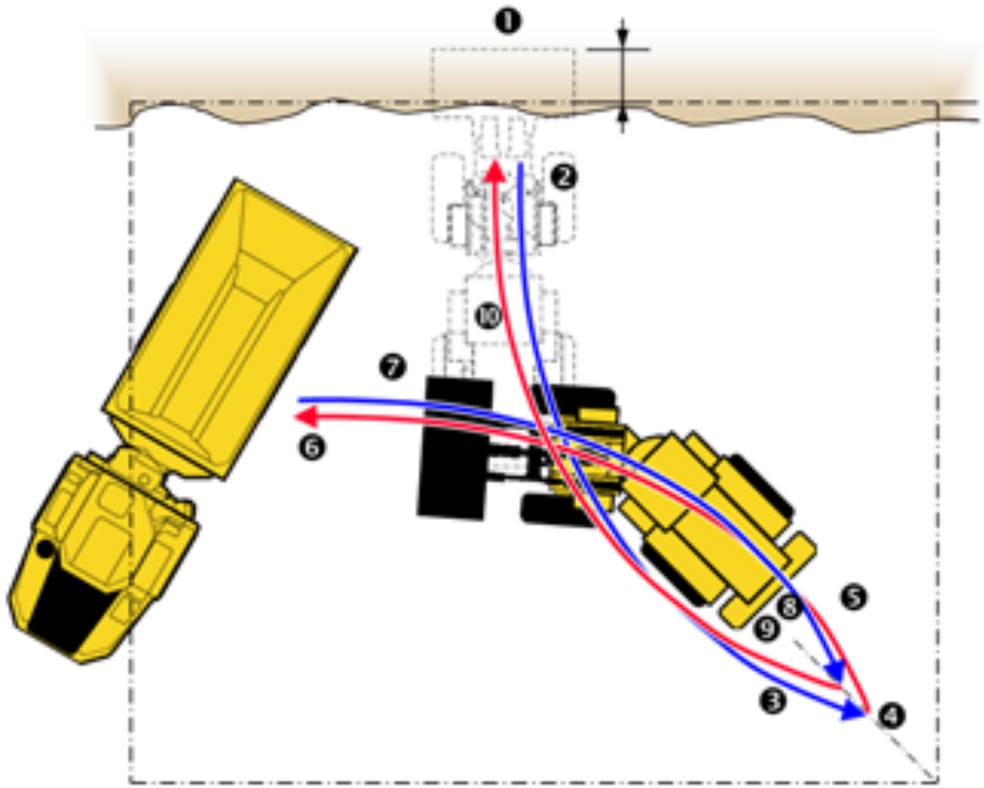
Innovation – Changed Driver Instructions





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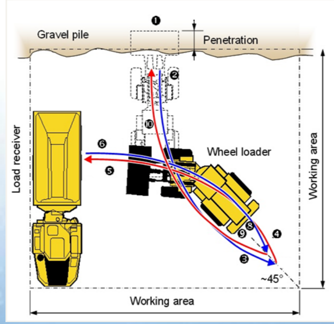
Special Thanks to:

Jonas Larsson, PhD, Volvo CE

Anders Froberg, PhD, Volvo CE

Vaheed Nezhadali, PhD Student, Vehicular Systems, LiU



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Publications for futher reading

- 1- **Parallel Multiple-Shooting and Collocation Optimization with OpenModelica**. Bernhard Bachmann, Lennart Ochel, Vitalij Ruge, Mahder Gebremedhin, Peter Fritzson, *Vaheed Nezhadali*, Lars Eriksson, and Martin Sivertsson (2012).

  In: Modelica 2012 -- 9th International Modelica Conference. Munich, Germany.

- 2 - **Modeling and Optimal Control of a Wheel Loader in the Lift-Transport Section of the Short Loading Cycle.**

  Vaheed Nezhadali, and Lars Eriksson.
  In: 7th IFAC Symposium on Advances in Automotive Control. Tokyo, Japan.

- 3 - **Optimal Control of Wheel Loader Operation in the Short Loading Cycle Using Two Braking Alternatives.**

  Vaheed Nezhadali, and Lars Eriksson.
  In: IEEE VPPC 2013 - The 9th IEEE Vehicle Power and Propulsion Conference. Beijing, China.

- 4 - **Optimal lifting and Path Profiles for a Wheel Loader Considering Engine and Turbo Limitations.**

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  In: Optimization and Optimal Control in Automotive Systems, In Lecture Notes in Control Sciences, Editors: L. del Re, I. Kolmanovsky, M. Steinbuch and H. Waschl. Springer.

- 5- **Turbocharger Dynamics Influence on Optimal Control of Diesel Engine Powered Systems.**

  Vaheed Nezhadali, Martin Sivertsson and Lars Eriksson

  In: SAE World Congress 2014, Detroit, USA.

- 6 - **Wheel loader optimal transients in the short loading cycle.**

  Vaheed Nezhadali, Lars Eriksson.
  The 19th IFAC World Congress 2014, South Africa.

Outline - Conclusions

- Numerical Optimal Control
  - Tools are now mature
  - Solve industrially relevant problems
    - Large size of the state vector
    - Significant nonlinearities
  - Impact on product development beside control
  - Point out counter-intuitive but optimal solutions
- Relevant models, tools, and problems accelerate innovation.

Thank You for Your Attention!

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