# Fuel-optimal Control of Heavy Trucks

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October 12, 2009

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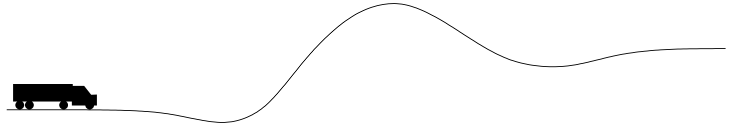
## Objective



Scenario

- Long-haulage heavy truck on open road
- An on-board road topography map

Controls

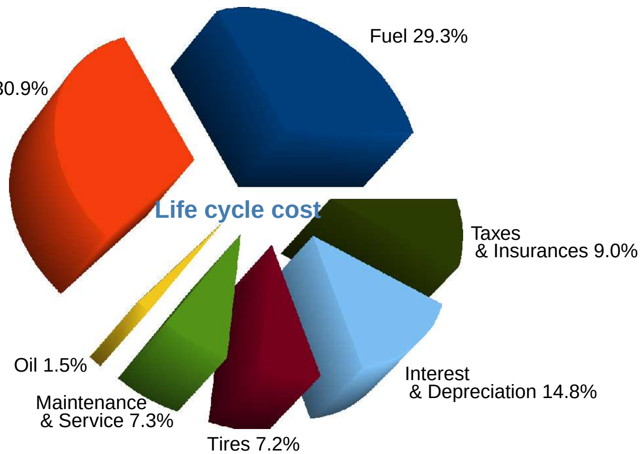
- Engine and brake torque (continuous)
- Gear ratio selection (discrete)

Minimum-fuel strategy for a drive mission with a given maximum trip time

$$\text{minimize } M$$
$$\text{subject to } T \leq T_0$$



## Motivation : Cost




An average class 8

- travels 150,000 km per year
- consumes 32.5 liter per 100 km

in Europe according to (Schittler, 2003)



## Motivation : Environment

Class 8 trucks

- typically travels at operating points with high efficiency
- on the other hand, they
  - consume 68 % of all commercial truck fuel used
  - 70 % of this amount is spent traveling on open road with a trip length of more than 100 miles (161 km)

In the U.S. according to (Bradley, 2000)

Summary

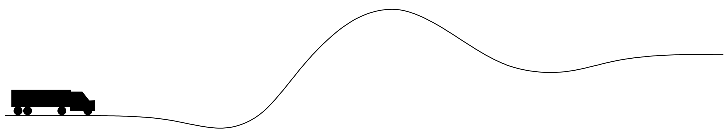
- Fuel is a large share of the life cycle cost
- Any technology that improves truck efficiency will have the best benefit for long-haul class 8 trucks

## Outline

- Background
- Introduction
- An Efficient Algorithm
- Experimental Evaluation
- Concluding Remarks



## Objective



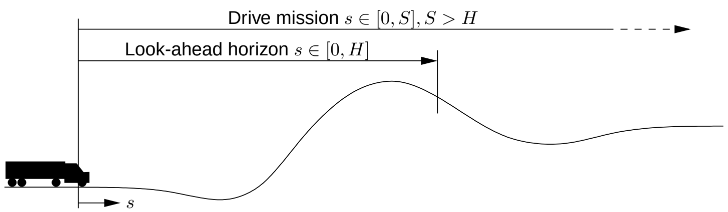
Minimum-fuel strategy for a drive mission with a given maximum trip time

$$\text{minimize } M$$
$$\text{subject to } \; T \leq T_0$$

- Conditions change during a drive mission
  - Disturbances such as delays
  - Changed parameters such as the mass
- Efficient approach is to consider a truncated horizon, a receding horizon approach



## Receding Horizon




The criterion is defined for $s \in [0, S]$: $\quad J = \min M(S)$

but we consider it for $s \in [0, H]$: $\quad \approx \min M(H) + \tilde{R}(x(H))$

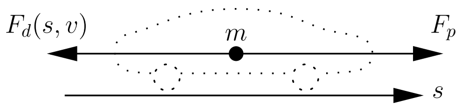
where $\tilde{R}$ is an estimate of the residual cost and a function of the terminal state $x(H)$.

**Objective defined**

The problem is to find the fuel-optimal control law for a finite horizon



## A Generic Analysis




$$mv\frac{dv}{ds} = F_p - F_d(s, v)$$

**Minimize the Propulsive Energy**

$$\min_{v(s)} W = \int_0^S F_p \, ds = \int_0^S \left( mv\frac{dv}{ds} + F_d(s, v) \right) ds$$
$$\text{subject to } \int_0^S \frac{ds}{v} \leq T_0$$

Using calculus of variations, the solution is shown to be a constant speed level $v > 0$, if we assume that

$$\frac{\partial F_d}{\partial v} \geq 0 \quad \text{and} \quad F_d(s, v) = f_1(s) + f_2(v).$$

## Key Features

The power to mass ratio makes

- moderate slopes significant
- velocity variations inevitable
- gear shifts necessary

$\Rightarrow$ Potential to reduce the fuel consumption.

**Some challenges**

- Already highly fuel-efficient
- Both real and integer variables
- A position-variant control law $u(x, s)$ is expected
- Real-time requirements



## Outline





## An Efficient Algorithm

- Current main challenge is to find the solution efficiently
- We propose an algorithm based on dynamic programming (DP)

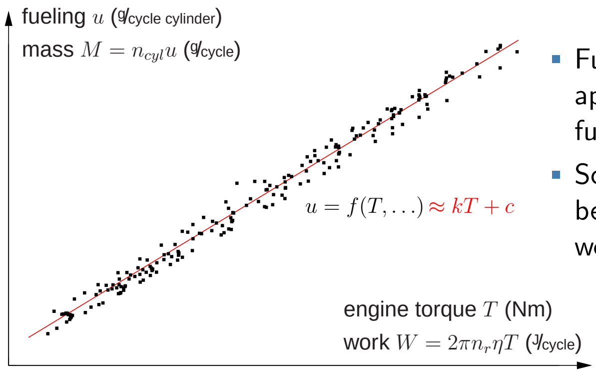
- Exponential increase of complexity in DP due to continuous variables
  - No issue here since the dimension is low
- Favorable linear growth with increasing horizon
  - A rather long horizon is needed
  - Alternative methods typically give a complex combinatorial problem due to integer variables
- Allows general modeling

**Approaches**

- Shorter horizon
  - Better estimate of the residual cost at the end of the horizon
- Fewer grid points
  - Lowering the dimension and reducing the search space
- Coarse grid and interpolation together with simple integration
  - An analysis of errors due to discretization and interpolation shows that



## Residual Cost




- Fueling $u$ versus torque $T$ is approximately an affine function with gradient $k$
- Scaling gives the relation between fuel mass $M$ and work $W$. The gradient is

$$\gamma = k \frac{n_{cyl}}{2\pi n_r \eta} \quad (\text{g/J})$$

$$\Delta M \approx \gamma \Delta W$$

## Residual Cost

- A change in kinetic energy $\Delta e$ at the end of the horizon is approximately proportional to a fuel mass

$$\Delta M \approx \gamma \Delta e$$

- This reflects that kinetic energy at the end of the horizon can be used to save fuel in the future
- With this assumption, the residual cost is

$$\tilde{R} = C - \gamma e$$

where $C$ can be chosen to zero.

- We have also shown that this is accurate in the unconstrained case
- For the general case, numerical results show that this is reasonable



## Lowering The Dimension : Reformulation

$$J = \min_{T=T_0} M \qquad \text{(P1)}$$

$$\begin{bmatrix} t \\ v \\ g \end{bmatrix}' = f(s, v, g, u)$$

$$J = \min M + \beta T \qquad \text{(P2)}$$

$$\begin{bmatrix} v \\ g \end{bmatrix}' = \tilde{f}(s, v, g, u)$$

For a given $\beta$, the solution for (P2) gives a trip time $T = T(\beta)$. If we find $\beta$ such that $T(\beta) = T_0$, then we have the solution for (P1) as well.

Time is no longer necessary as a state, instead we have to find $\beta$.



## Lowering The Dimension : Finding $\beta$

- The function $T(\beta)$ is monotonically decreasing

$$T(\beta_2) \leq T(\beta_1) \text{ iff } \beta_2 \geq \beta_1 > 0$$

- $\beta$ could be found by, e.g., simple shooting methods
- We derive an approximate value of $\beta$

A vehicle travels at speed $\hat{v}$ on level road for $\Delta s$. Then, typically $F_d(s, v) = F_d(v)$ and we have $J(\hat{v}) = M + \beta T$ where

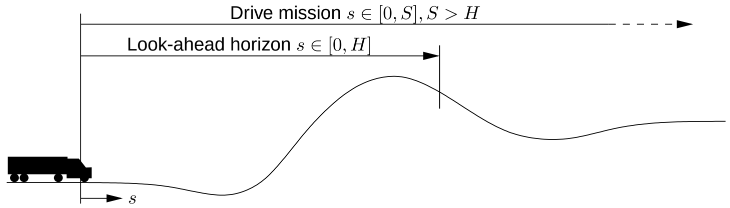
$$M = \gamma \Delta W = \gamma F_d(\hat{v}) \Delta s \quad \text{and} \quad T = \frac{\Delta s}{\hat{v}}$$

In a stationary point, $J'(\hat{v}) = 0$, it holds that $\beta = \gamma \hat{v}^2 F_d'(\hat{v})$, where typically $F_d'(\hat{v}) = F_{\text{air}}'(\hat{v})$

$$\beta = 2\gamma P_{\text{air}}(\hat{v}) \quad (\text{g/s})$$



## Algorithm : Summary




- We consider (P2) for $s \in [0, H]$, i.e.,

$$\min \left\{ M + \beta T + \tilde{R} \right\}$$

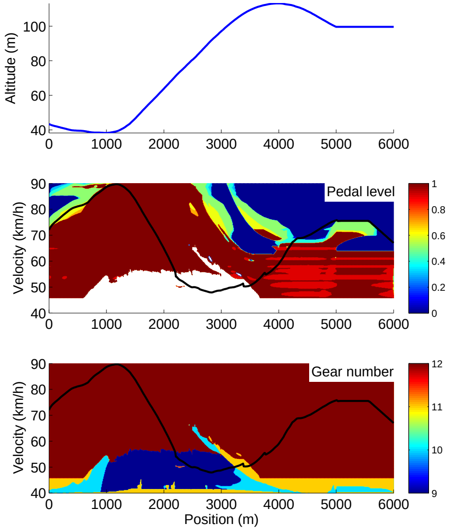
where $\tilde{R} = -\gamma e(H)$ and $\beta = 2\gamma P_{\text{air}}(\hat{v})$.

- Solved through DP
- Energy formulation of the dynamics makes it possible to use coarse grids together with linear interpolation and Euler forward integration

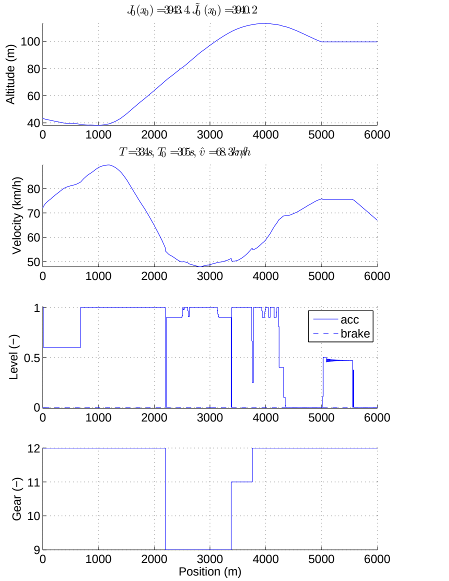
E. Hellström, J. Åslund, and L. Nielsen.
Design of an efficient algorithm for fuel-optimal look-ahead control.
Solicited for Control Engineering Practice.

## A Solution

The control law $u = \mu(s, x)$ for $g = 12$




A particular solution for $x_0 = [72, 12]$






## Outline

- Background
- Introduction
- An Efficient Algorithm
- **Experimental Evaluation**
- Concluding Remarks



## Evaluation Setup

- Collaboration with SCANIA
- GPS and road database on board

**Louice**

- About 40,000 kg
- 5 cylinder, 9 liter engine
- Max. 1550 Nm, 310 Hp
- 12-speed transmission

- 84 km/h ± 5 km/h
- 1500 m horizon

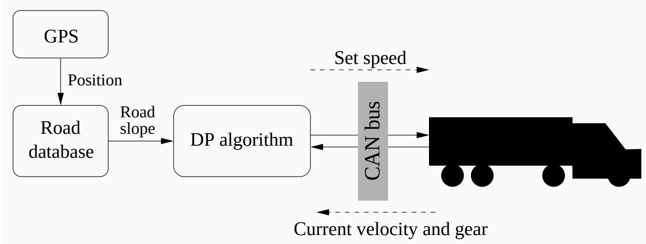
YouTube Search for Look-ahead Control

E. Hellström, M. Ivarsson, J. Åslund, and L. Nielsen.
Look-ahead control for heavy trucks to minimize trip time and fuel consumption.
Control Engineering Practice, 17(2):245–254, 2009.



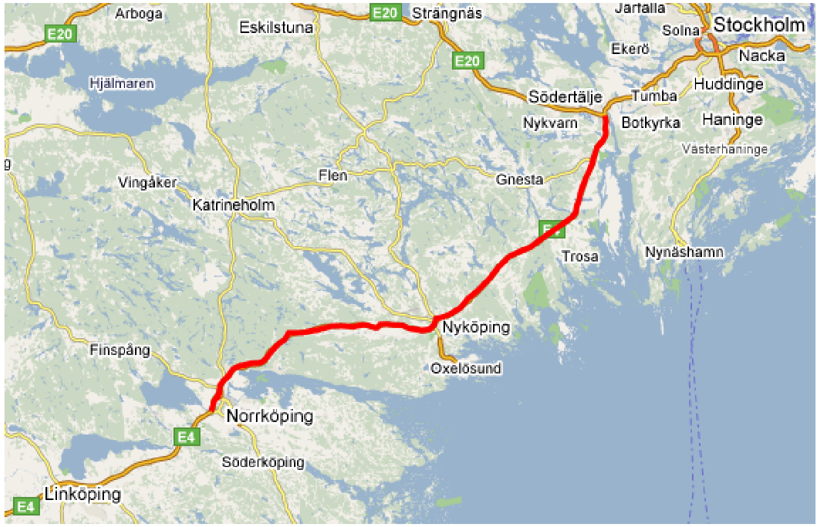
## Evaluation Setup : Interface

- Feed the cruise controller with set speeds
- Model the automatic gear shift system




## Trial Route

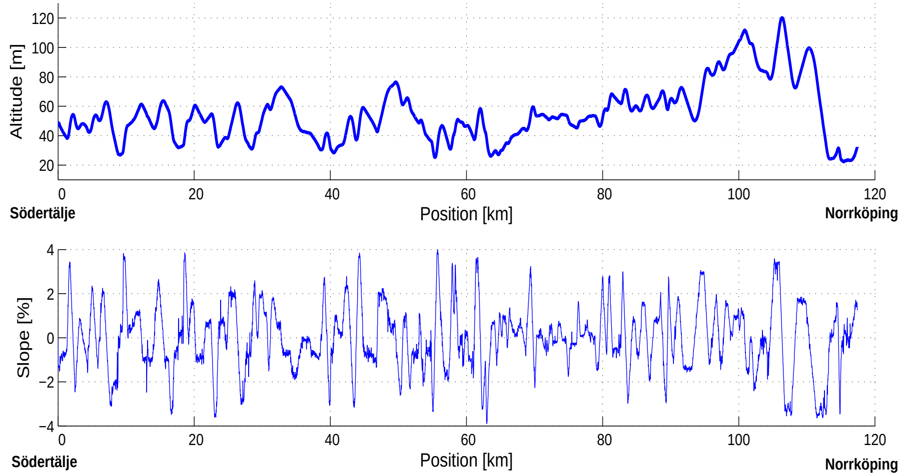
- 120 km highway segment






## Trial Route : Topography

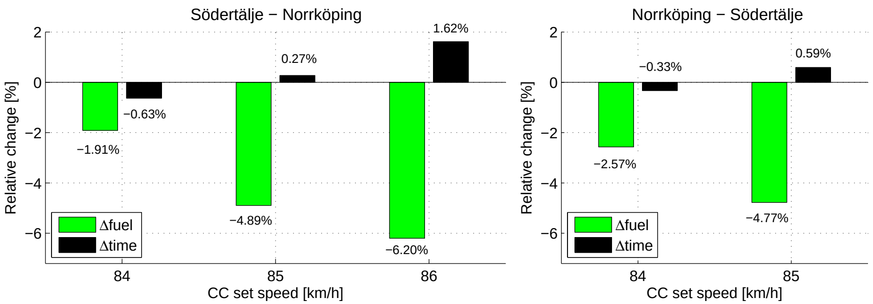
- Moderate slopes
- Light to moderate traffic






## Experimental Results

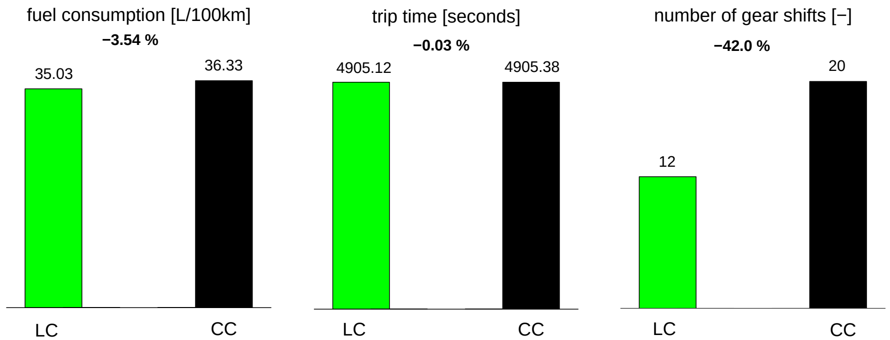
- Five comparative runs
  - Algorithm parameters constant
  - Cruise controller set point varied



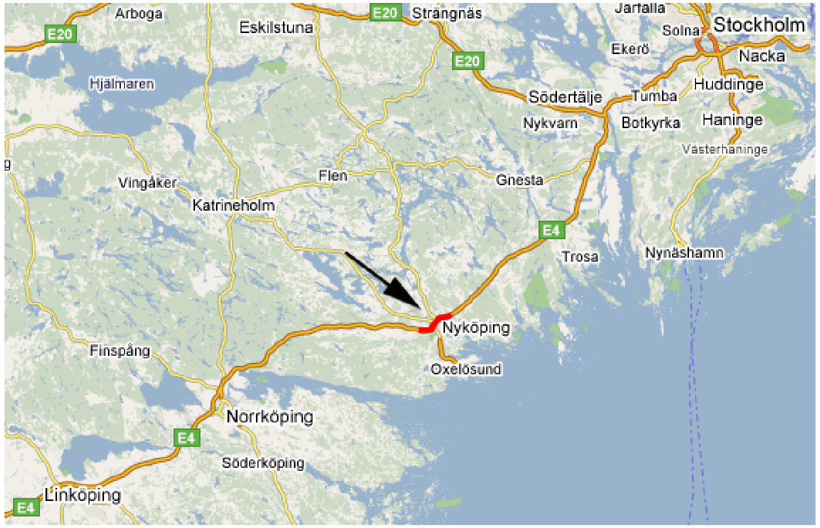



## Average Results

- Average over four runs back and forth

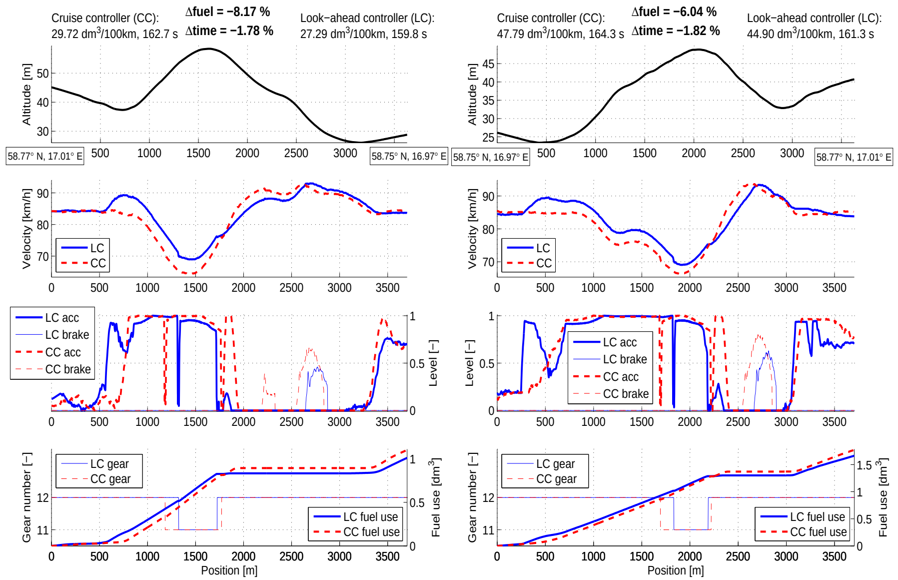


## The Hållet Segment



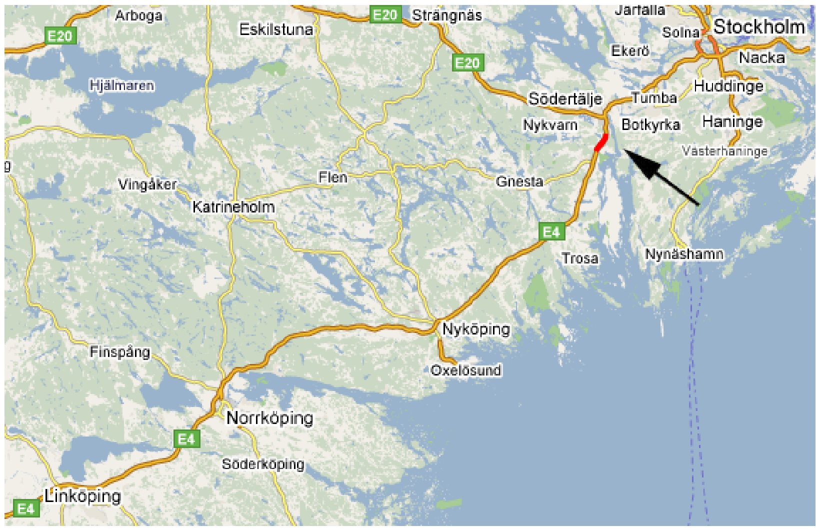



## The Hållet Segment : Characteristics



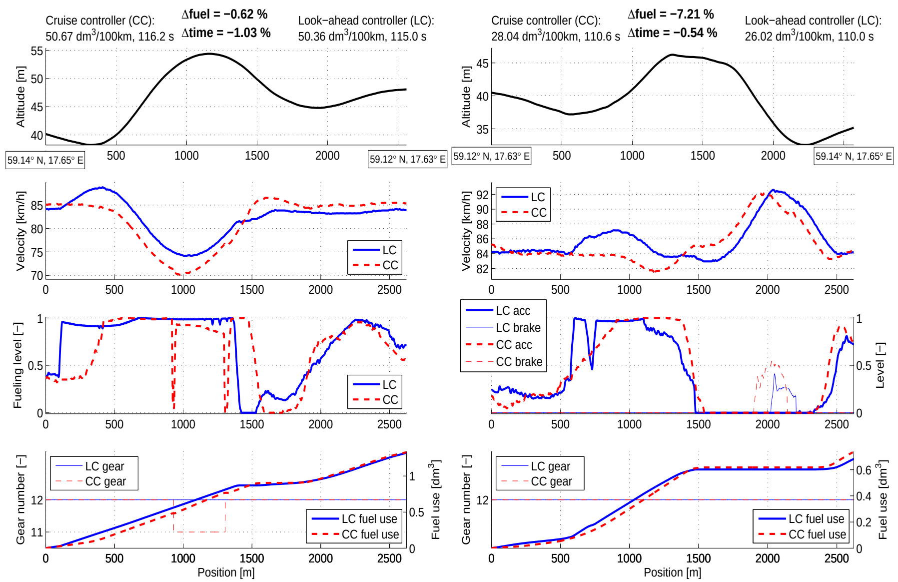



## The Järna Segment






## The Järna Segment : Characteristics



## Concluding Remarks

- An efficient optimization algorithm is tailored based on DP
  - Energy formulation of the dynamics is a key point
  - Sufficiently low complexity make experimental evaluation feasible
- The look-ahead control strategy is evaluated in trial runs
  - Significant reduction of the fuel consumption is demonstrated
  - The behavior is perceived as natural and comfortable
  - Quantification of the optimal characteristics



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## An Energy Perspective