PUBLIC RESEARCH CENTRE HENRI TUDOR

UNIVERSITÉ DU LUXEMBOURG

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JOHNS HOPKINS UNIVERSITY

A coupled energy & air quality model for lowest cost energy solutions, respecting air quality constraints: development and initial results

Dan Zachary

May 6, 2014

www.tudor.lu

NOAA SEMINAR - NCWCP Conference Center *College Park*

Introduction to energy – air quality modeling

The model

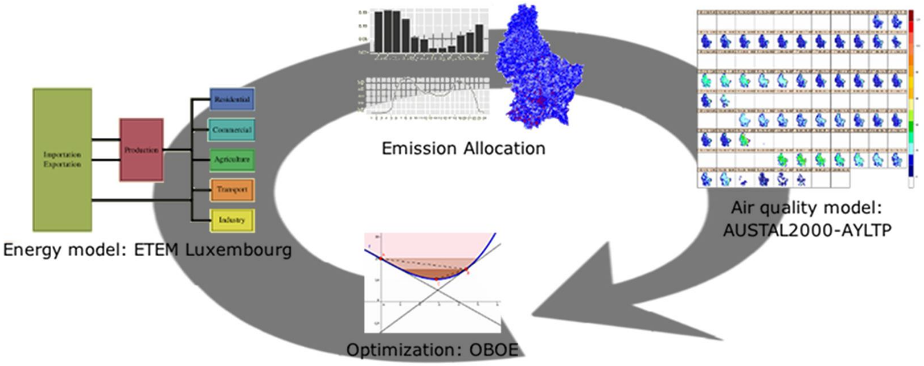
An illustrative example

Results

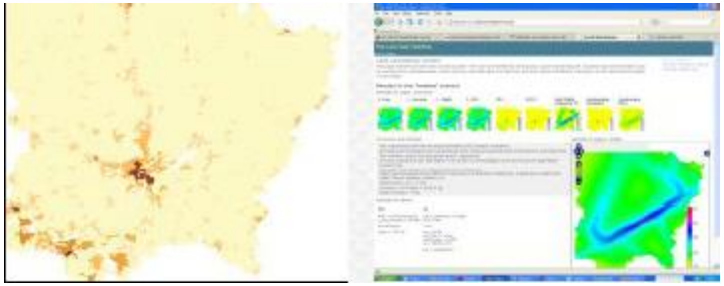
Daniel Zachary (Applied Physicist, Mathematician)
Ulrich Leopold (Geographer, finishing PhD)
Olivier Baume (Computer Scientist)
Luis Alexandre Duque Moreira De Sousa (GIS, Computer Scientist, PhD student)
Chris Eykamp (GIS expert, programer)
Chris Braun(GIS expert, geographer)
Lara Reis (Atmospheric scientist) - now in Milan, Italy
Laurent Drouet (Computational scientist) – now in Milan, Italy

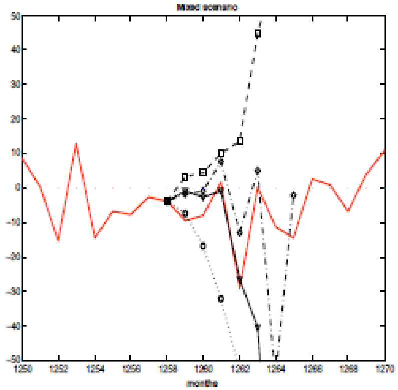
TUDOR Modeling Group – Research snapshot

Integrated assessment: Energy-AQ

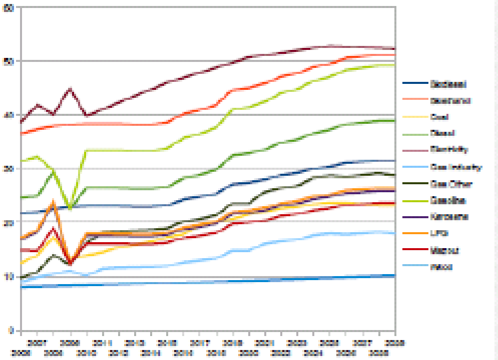


Integrated assessment: Impact



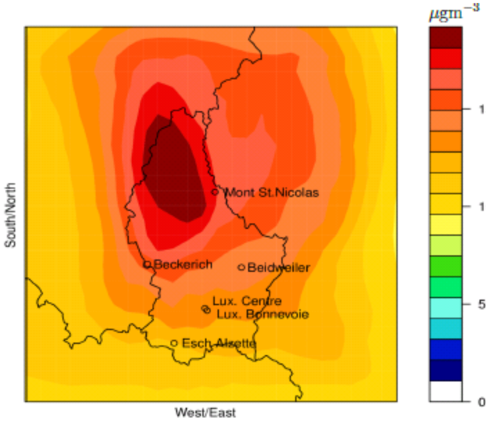


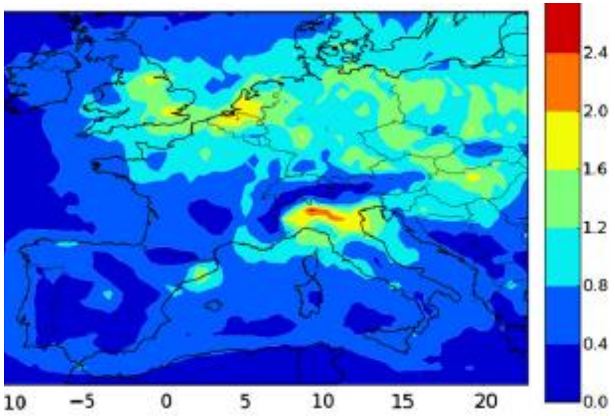
Bayesian risk (atmospheric forecasting)



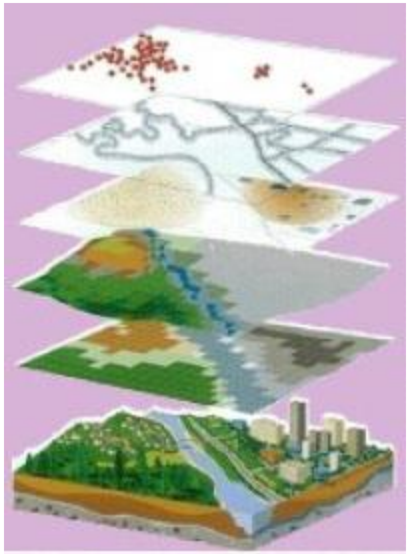
Energy projections

AQ





Geospatial analysis



Europe

Serbia and Montenegro have asserted the formation of a joint independent state, but this entity has not been formally recognized as a state by the United States.

*F.Y.R.O.M. - The Former Yugoslav Republic of Macedonia

Scale 1:19,500,000

Lambert Conformal Conic Projection, standart parallels 40°N and 56°N

802377 (R01083) 5-95

Air pollution – a major concern

- The London smog disaster 1952, brought attention to the damaging effects of air pollution.

- There is a negative relation of air pollution with human health, resulting in an increase of morbidity and mortality.

  [Ström et al., 1994; Solé et al.,2007; West et al., 2007; Laaidi et al., 2011; Rückerl et al., 2011; Tzivian, 2011].

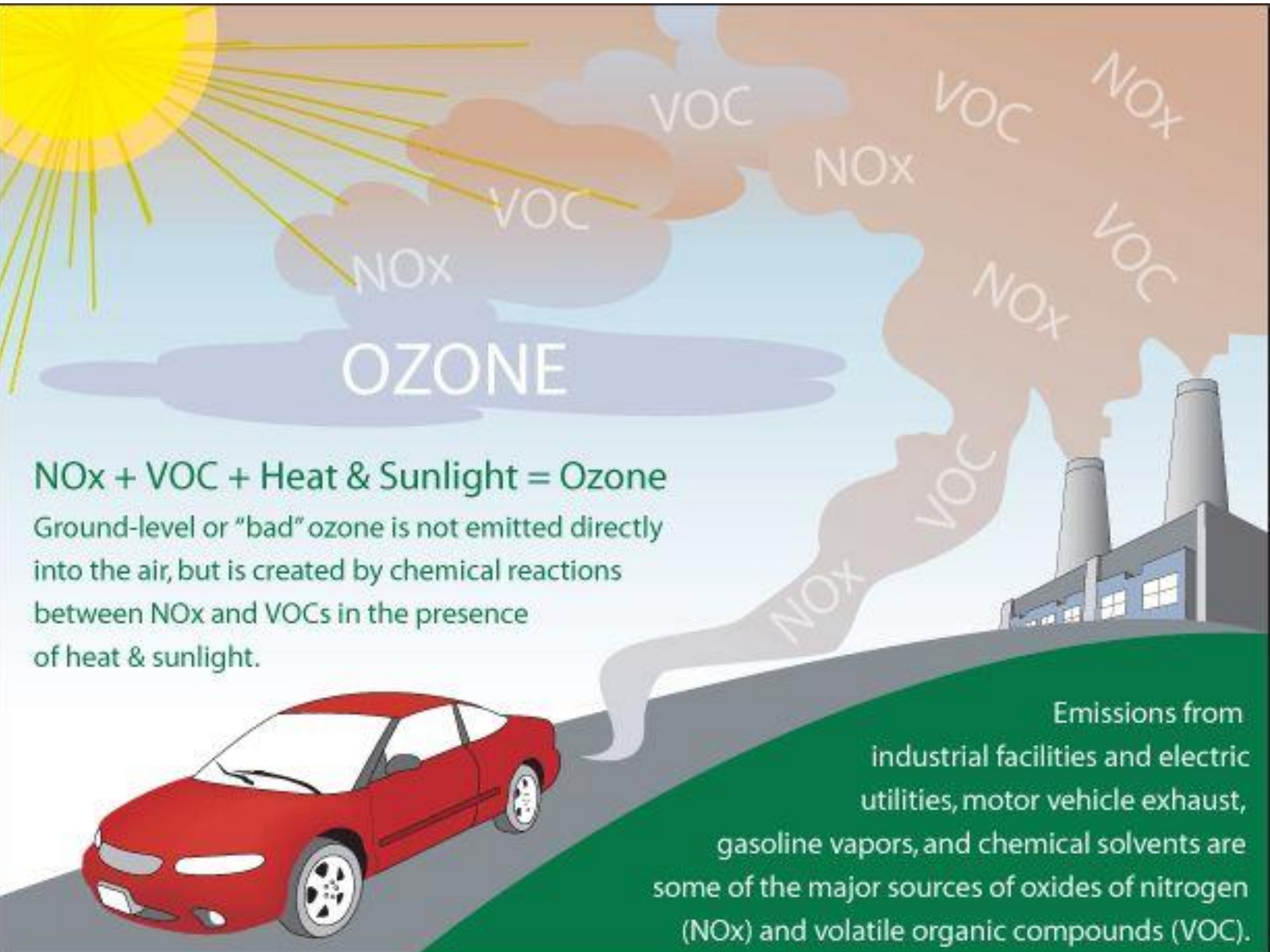
- *"Urban outdoor air pollution is estimated to cause 1.3 million deaths worldwide per year."* [World Health Organization, 2011].

Ref. Lara Reis, Ph.D. Defense

A need for integrated solutions

- *"Indeed air pollutant concentrations are still too high and harm our health and the ecosystems we depend on."*

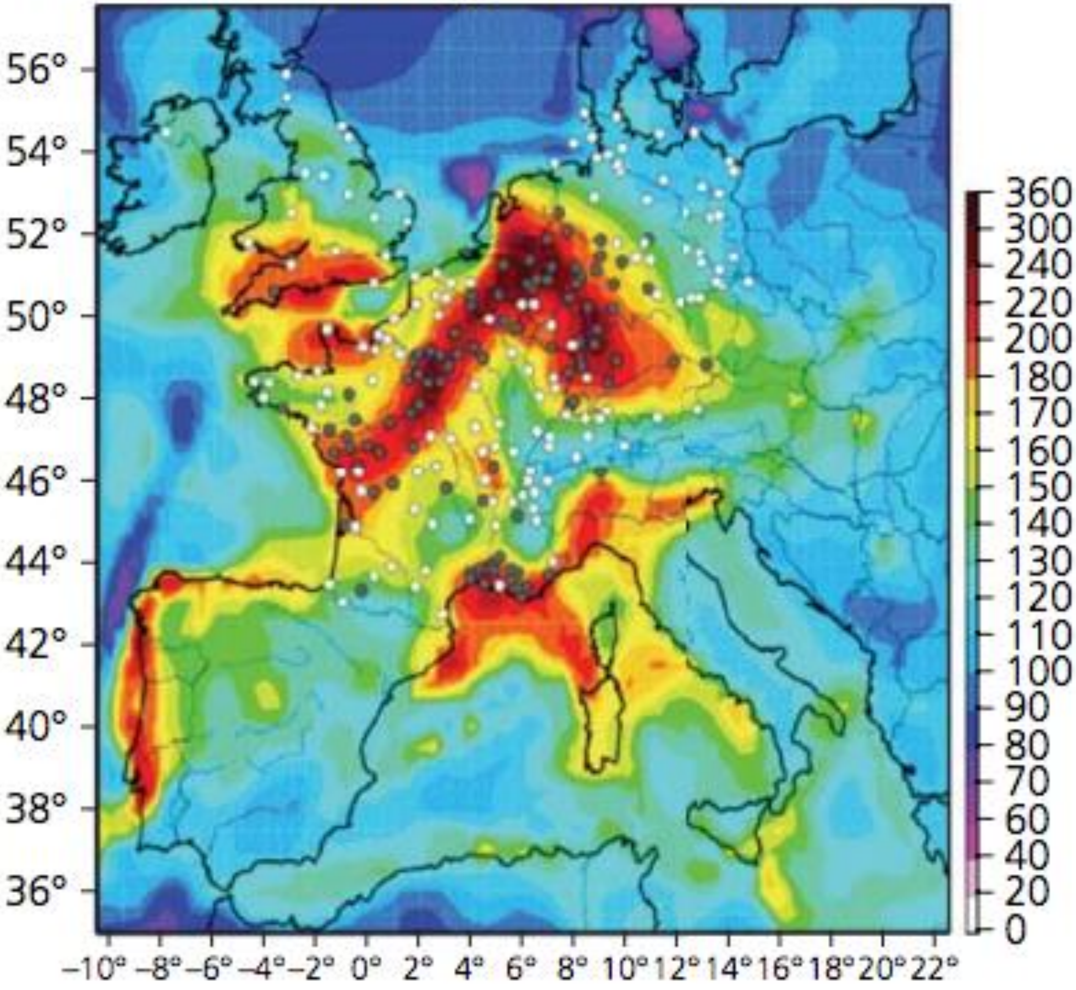
  [European Environment Agency, 2012].
- Ozone (O_3) is one of the most problematic and harmful pollutants. Exposure to O_3 has generally not decreased since 2001. [European Environment Agency, 2012].
- European legislation on air quality has been developed and is becoming more and more strict.
- ***"European policies and measures increasingly seek to maximise co-benefits, managing air pollutant and greenhouse gas emissions at the least cost to society."*** [European Environment Agency, 2011].



NOx + VOC + Heat & Sunlight = Ozone

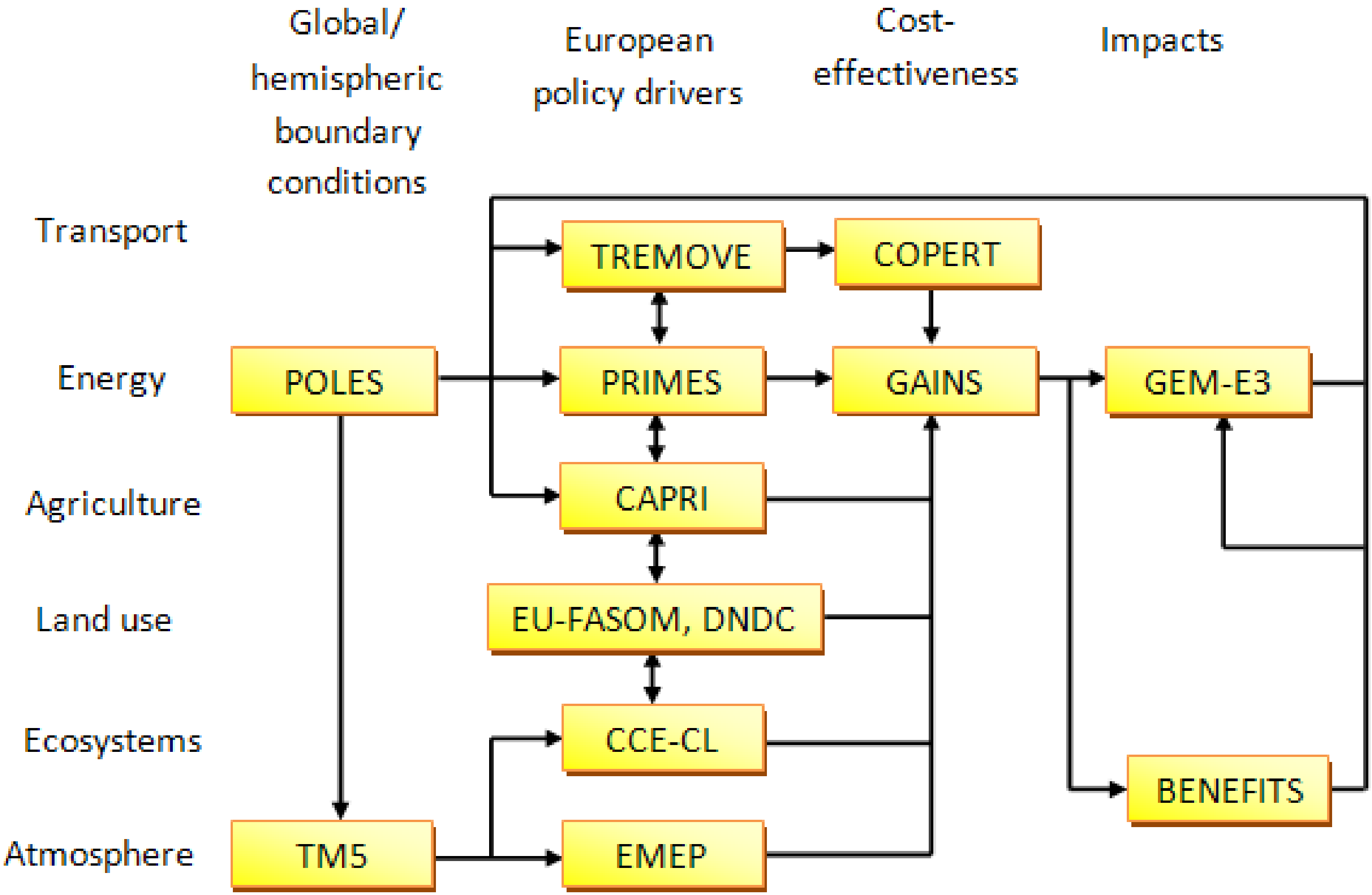
Ground-level or "bad" ozone is not emitted directly into the air, but is created by chemical reactions between NOx and VOCs in the presence of heat & sunlight.

Emissions from industrial facilities and electric utilities, motor vehicle exhaust, gasoline vapors, and chemical solvents are some of the major sources of oxides of nitrogen (NOx) and volatile organic compounds (VOC).



(b) Surface Ozone [μg/m^3) 08/08/2003 41hut

Some models explore solutions via simulation – e.g. (EC4MACS)



Global/ hemispheric boundary conditions

European policy drivers

Cost-effectiveness

Impacts

Transport

Energy

Agriculture

Land use

Ecosystems

Atmosphere

TREMOVE

COPERT

POLES

PRIMES

GAINS

GEM-E3

CAPRI

EU-FASOM, DNDC

CCE-CL

BENEFITS

TM5

EMEP

Introduction / Motivation

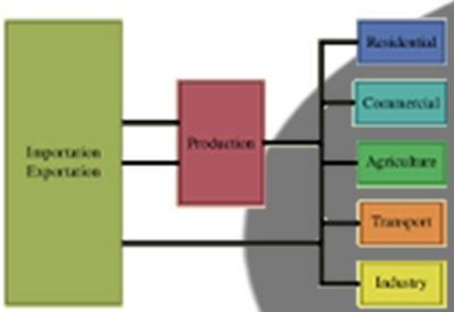
The model (Energy-emissions / Air Quality)

An illustrative example

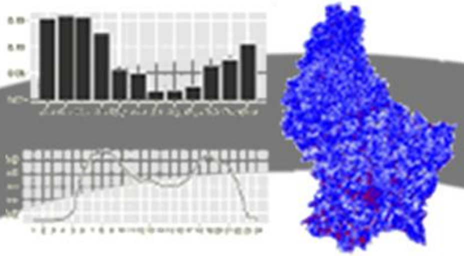
Results

The integrated assessment model – the LEAQ model

Energy Technology Environmental Model - ETEM



Energy model: ETEM Luxembourg



Emission Allocation

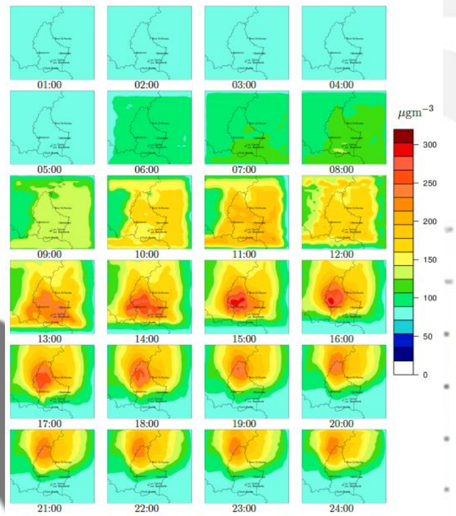
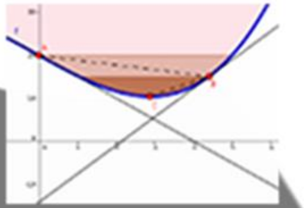
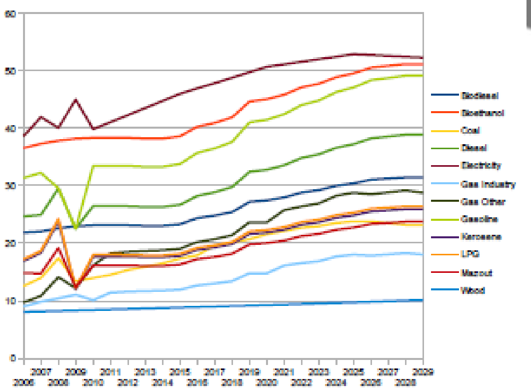


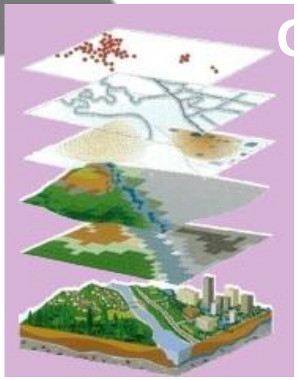
Figure 6.9: Spatial and hourly distribution of the predicted O_3 concentrations, by AUSTAL2000-AYLTP on July 19th, 2006.

Air quality model:
AUSTAL2000-AYLTP



Optimization

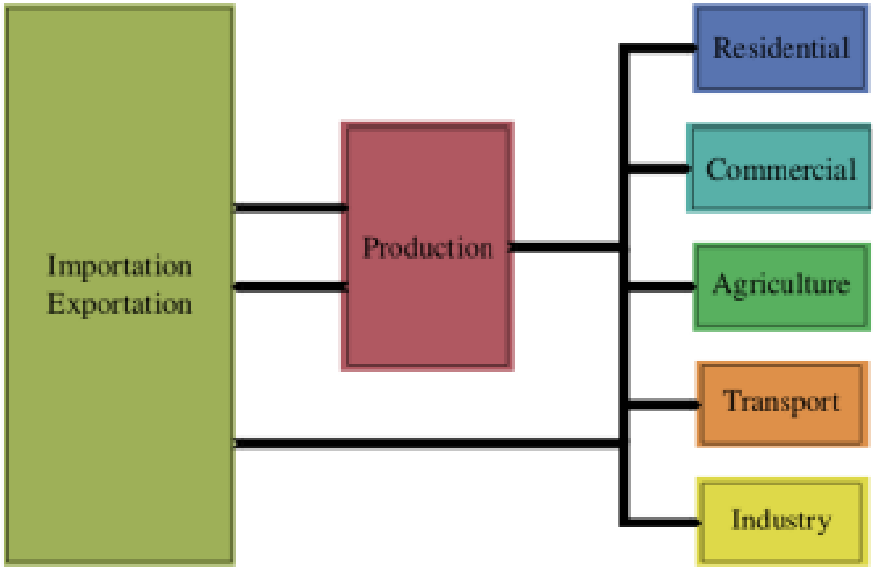




GIS / geospatial analysis tools

http://crteweb.tudor.lu/leaq/

The ETEM model



Refererence Energy System of Luxembourg

Energy Model

- Dynamic linear optimization
- End-use demands
- Future technologies
- Energy prices evolution
- Total energy system cost
- Energy policy assessment
- GHG (CO_2, CH_2, N_2O)
- Air pollutants (NO_x, VOC)

ETEM (Energy Technology Environmental Model)

- ETEM model (`http://www.ordecsys.com`)
- Implementation of MARKAL/TIMES in GMPL (LP)
- Energy system of Luxembourg ($\sim$ 100'000 rows/columns)
- Time horizon: 9 periods of 5 years (2005–2050)
- Minimize the total discounted energy cost s.t.
  - the demands in energy services are satisfied,
  - the commodity flows balance is respected;

$$\min_{\mathbf{x}}\{\mathbf{c}'\mathbf{x} \mid \mathbf{A}\mathbf{x} = \mathbf{b}, \mathbf{x} \geq 0\}$$

The ETEM model

```
###############
#             #
# ETEM model  #
#             #
###############
# Date     : 11/2008
# Version  : 2.0
# Authors  : L. Drouet et J. Thenie
# Language : GMPL
# command  : glpsol -m model_file.mod -d data_file.dat -y display_file.txt -o
output_file.txt
# example  : glpsol -m etem.mod -d geneva.dat

param nb_periods    >=1;
param period_length >=1;     # expressed in year.

set T := 1..nb_periods;      # time periods.
set L;                       # localization
set S;                       # slice periods
set P;                       # processes
set C;                       # commodities
set DEM within C;            # useful demands
set IMP within C;            # imported commodities
set EXP within C;            # exported commodities
set FLOW;                    # commodities groups labels
set FLOW_IN{P} within FLOW;  # incoming flows
set FLOW_OUT{P} within FLOW; # outcoming flows
set C_ITEMS{FLOW} within C;  # set of commodities
set P_MAP{L} within P;       # localization of processes
```

Plus about 350 more lines

The ETEM data

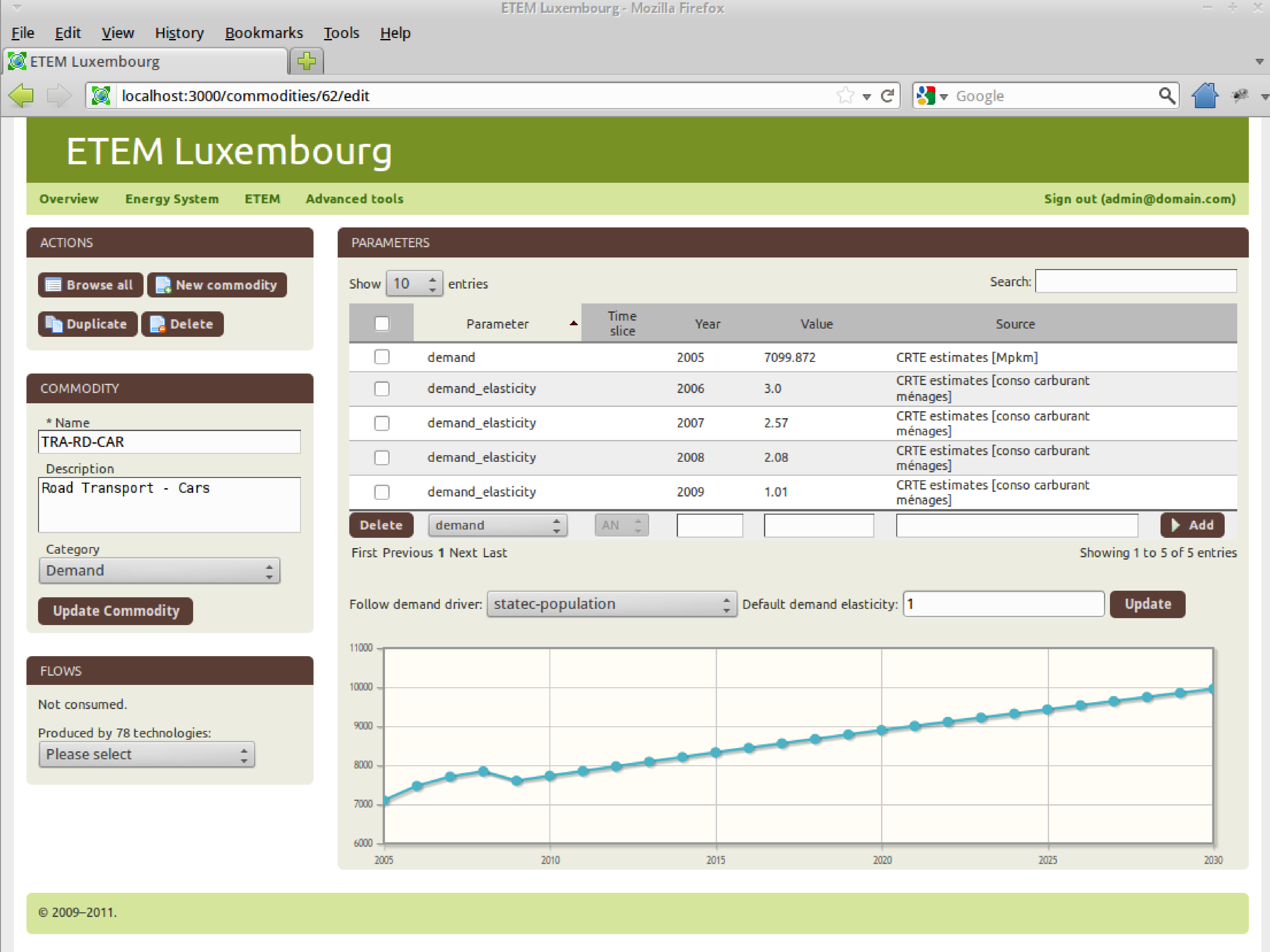
```
data;

# set of time slices
set S:=
WD     # Winter Day
WN     # Winter Night
SD     # Summer Day
SN     # Summer Night
ID     # Intermediate Day
IN;    # Intermediate Night

# set of localisations (cities)
set L:=
LUXEMBOURG
HAUTSURE
CADIOM;


# set of processes
set P:=
       # Electricity Industrial
I11    # Electrical appliances            # existing technology
I13    # El. savings industrial 2          #   new    technology
I14    # El. savings industrial 3          #   new    technology
I15    # El. savings industrial 4          #   new    technology
I1A    # El. savings heat pump              #   new    technology
I1B    # El. savings clim/air              #   new    technology
I1C    # El. savings cold                 #   new    technology
I1I    # El. savings compressor             #   new    technology
I1J    # El. savings pumps                 #   new    technology
I1K    # El. savings fax/photocopy            #   new    technology
       # LTH Industrial Area
IA1    # Electric                       #   new    technology
```

Plus about 2500 more lines



ETEM Luxembourg

Show 10 entries

☐	Parameter	Time slice	Year	Value	Source
☐	demand		2005	7099.872	CRTE estimates [Mpkm]
☐	demand_elasticity		2006	3.0	CRTE estimates [conso carburant ménages]
☐	demand_elasticity		2007	2.57	CRTE estimates [conso carburant ménages]
☐	demand_elasticity		2008	2.08	CRTE estimates [conso carburant ménages]
☐	demand_elasticity		2009	1.01	CRTE estimates [conso carburant ménages]

Delete | demand | AN | Add

Showing 1 to 5 of 5 entries

Follow demand driver: statec-population Default demand elasticity: 1

COMMODITY

* Name: TRA-RD-CAR

Description: Road Transport - Cars

Category: Demand

FLOWS

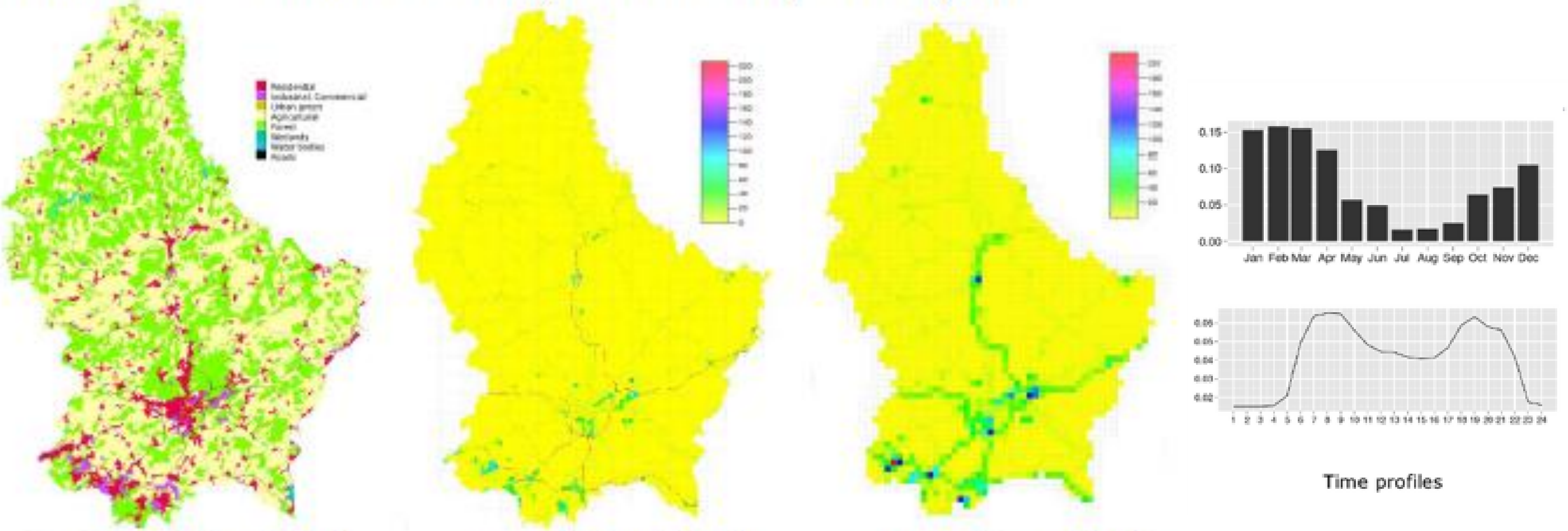
Not consumed.

Produced by 78 technologies: Please select

© 2009–2011.

Emissions

Sectoral emissions $\bar{e}$ are distributed over space and time to provide emissions rates at sources using land-use maps and spots.

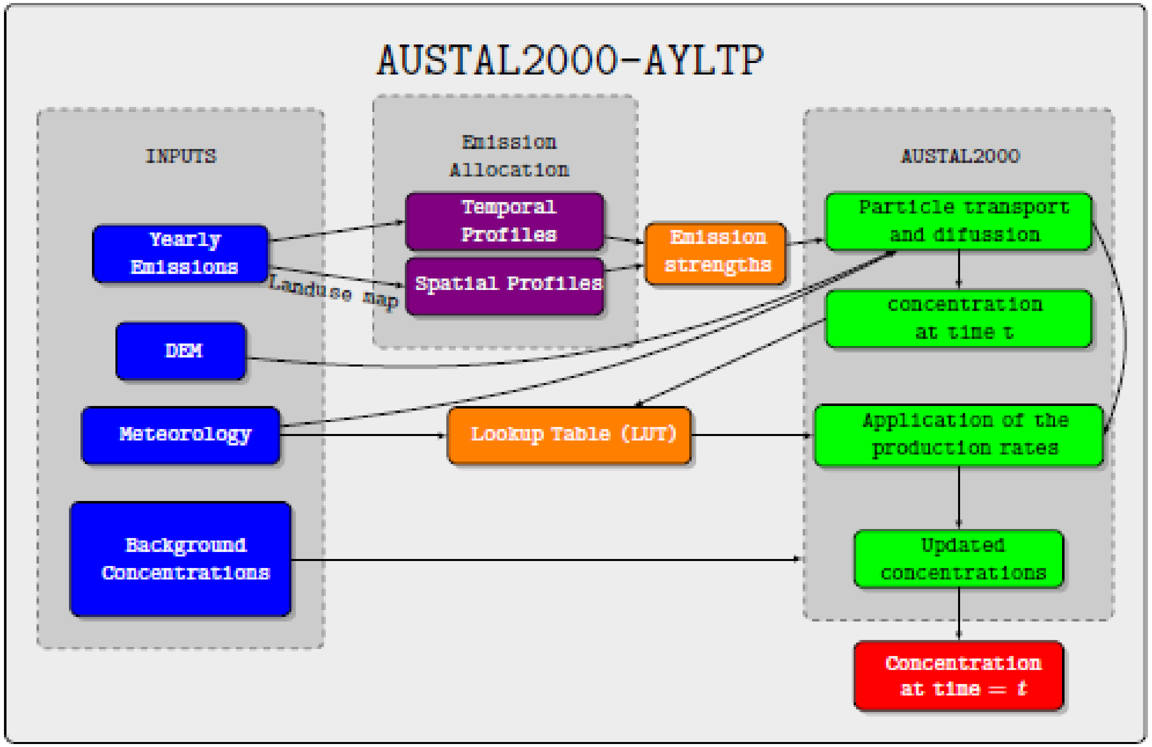


Time profiles

land-use (20mx20m) ⇒ sources (20mx20m) ⇒ sources (1kmx1km)

$$\bar{e} = \int_{S \times T} \mathbf{E}(t, s) \mathrm{d}s\mathrm{d}t$$

The air quality model



AOT: Average Over Threshold (60 ppb)

$$\mathrm{AOT}(\bar{e}) = \frac{1}{|S|}\frac{1}{t}\int_{S\times T} C_{O_3}(t,s;\bar{e})\,ds\,dt$$

Calculation time

Emission allocation + AYLTP + AOT calculation = 5 min

The air quality model – example of dynamics in a Lagrangian model

Brownian motion

$$x = \hat{x} + d(\hat{x}) + s$$

$\hat{x}$ particle location at time $t + \tau$

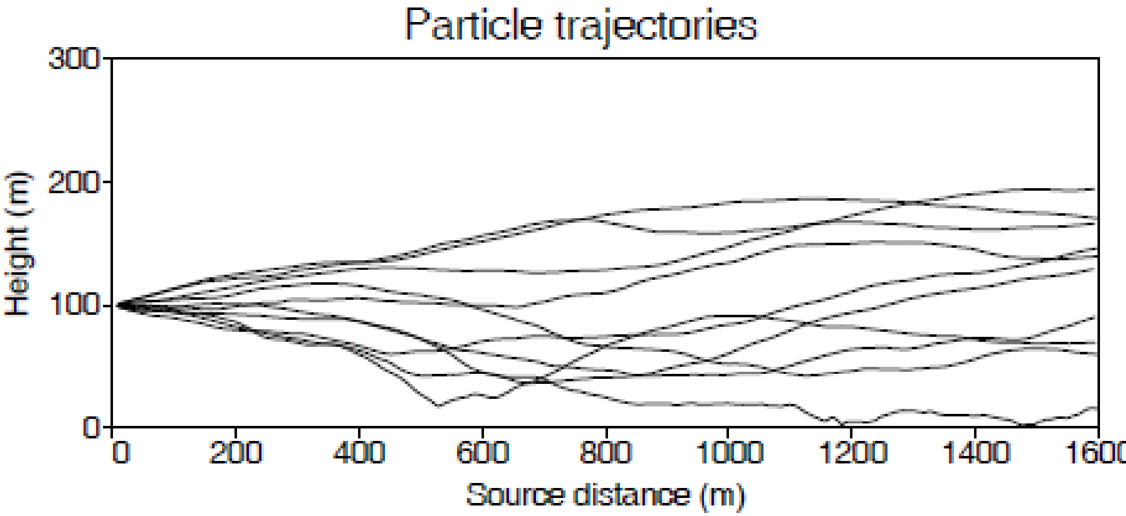
d deterministic displacement $\tau V(\hat{x})$,

s stochastic displacement with distribution function

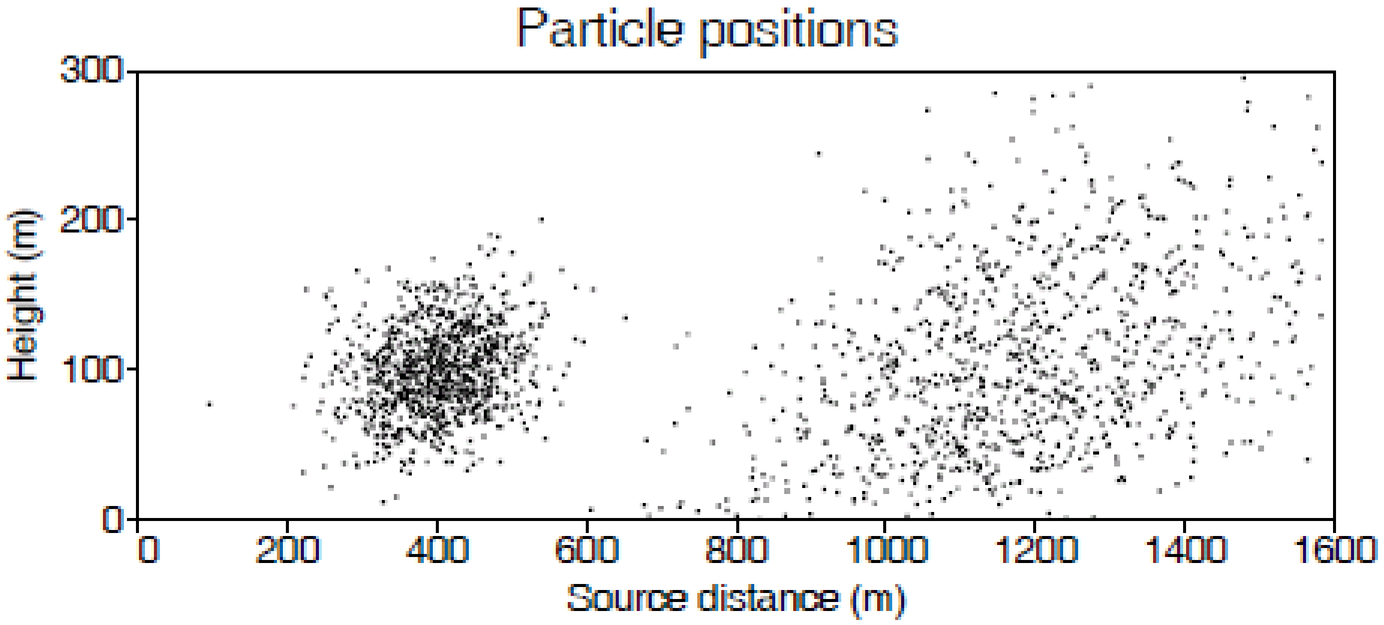
V particle velocity

Other dynamics included

- Brownian diffusion
- Brownian turbulence

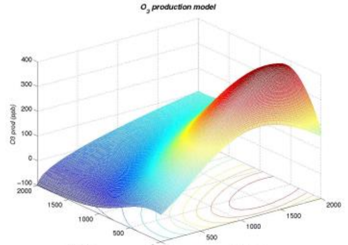


The air quality model – dynamics



A cloud of 1000 simulation particles emitted all at the same time at the height 100 m, shown 80 seconds after emission (left part of the picture) and 240 seconds after emission (right part). Note the effects of wind shear.

The air quality model



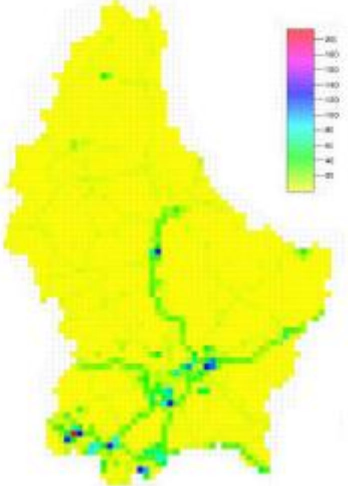
O$_3$

NOX VOC

...

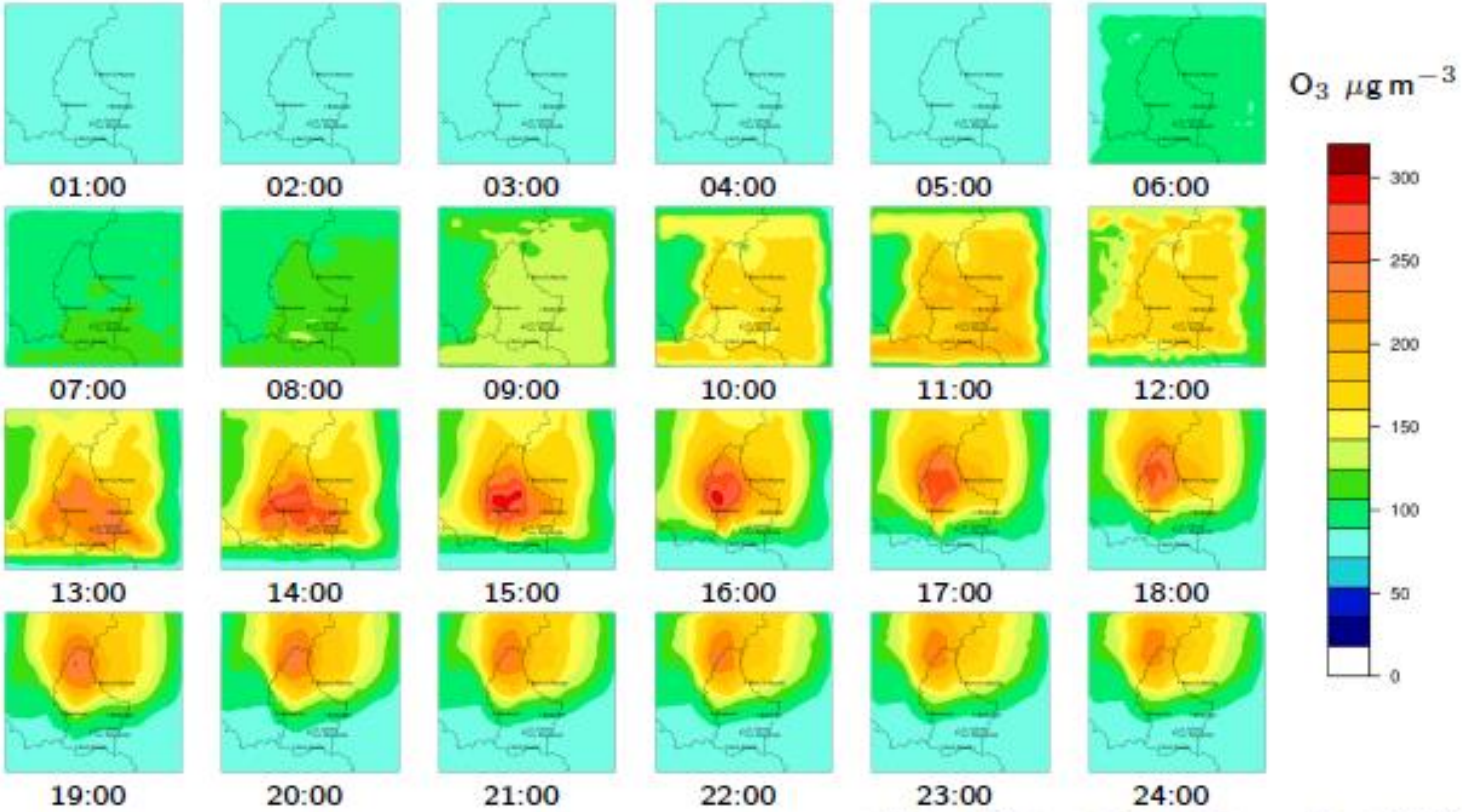
$$AOT = \frac{1}{T \times S} \int_0^T \int_S max(0, c(t, x; \bar{e}))dsdt$$

$$s = (x, y, z)$$



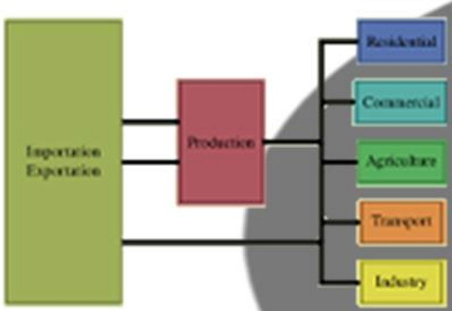
Day: - July 19th 2006

- high ozone concentration day
- ETEM emissions calibrated for 2006

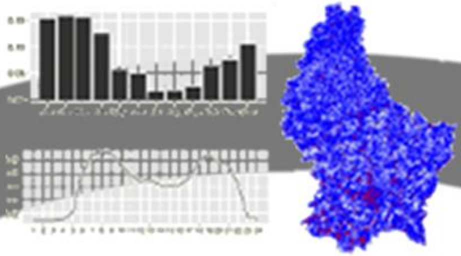


The integrated assessment model

Energy Technology
Environmental Model



Energy model: ETEM Luxembourg



Emission Allocation

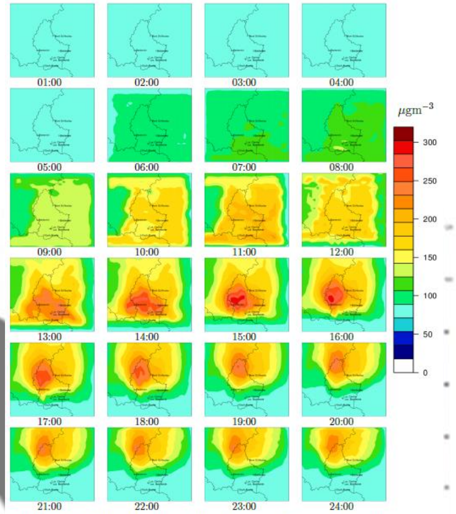
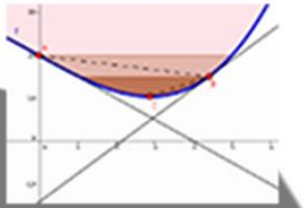
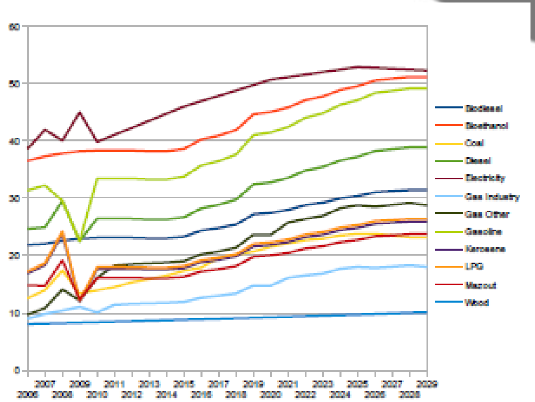


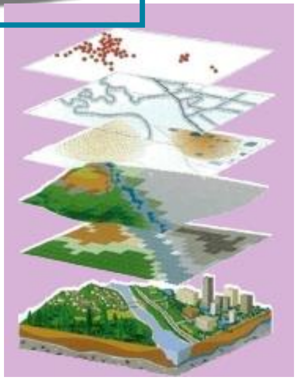
Figure 6.9: Spatial and hourly distribution of the predicted O_3 concentrations, by AUSTAL2000-AYLTP on July 19th, 2006.

Air quality model:
AUSTAL2000-AYLTP



Optimization: OBOE





GIS / geospatial analysis tools

http://crteweb.tudor.lu/leaq/

The coupled model – combining ETEM and AQ with OBOE

Cost minimization problem:

$$\text{Min}\ \{\gamma\ (e)\ :\ \text{AOT}(\bar{e},p)\ \leq\ \text{AOT}_{max}\}$$

$$\boxed{\gamma = \min\ \{c'x\ |\ Ax = b\ ,\ x \geq 0\}}$$

ETEM

p = pollution (O_3 concentration in ppb) level decision variable

$\bar{e}$ = emissions (tonnes per year) decision variable

AOT = Accumulated Ozone exposure over a Threshold

Introduction / Motivation

The model (Energy-emissions / Air Quality)

An illustrative example

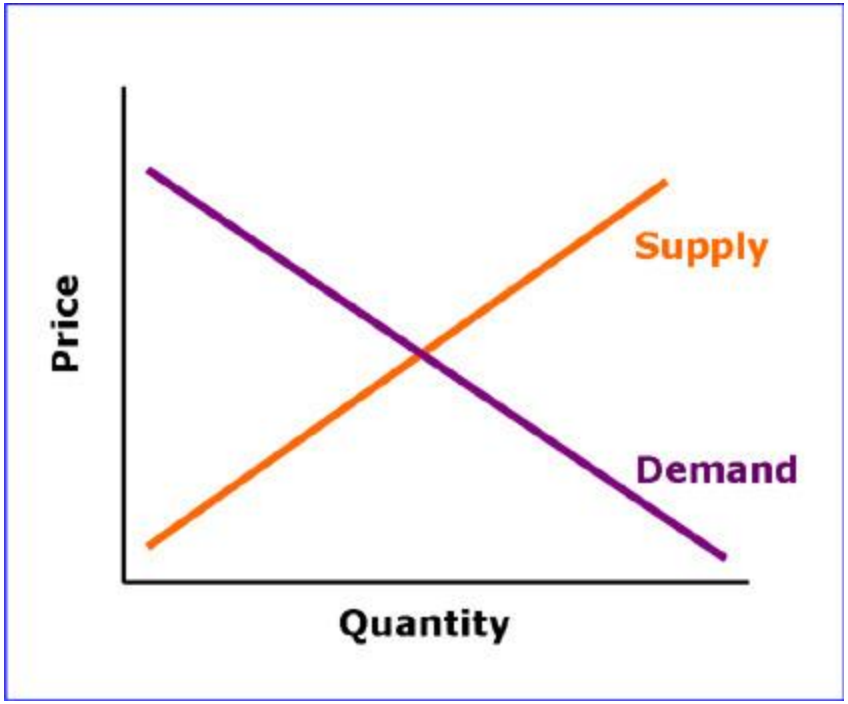
Results

Example – a very simple economy

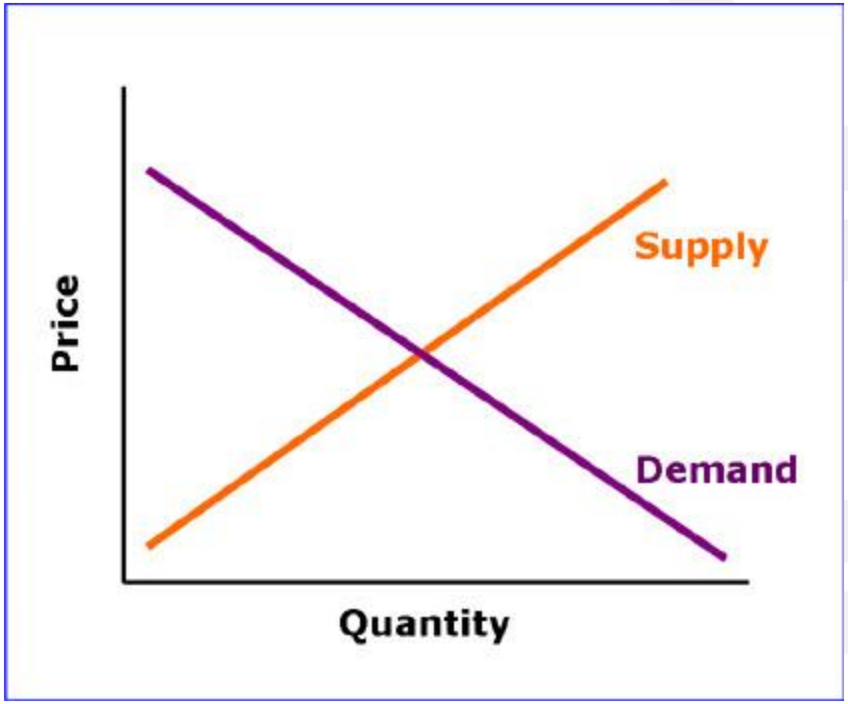
Car of type 1 – inexpensive, heavily polluting, maximum N_1

Car of type 2 – expensive, lightly polluting, maximum N_2

Supply & demand – for 2 types of cars

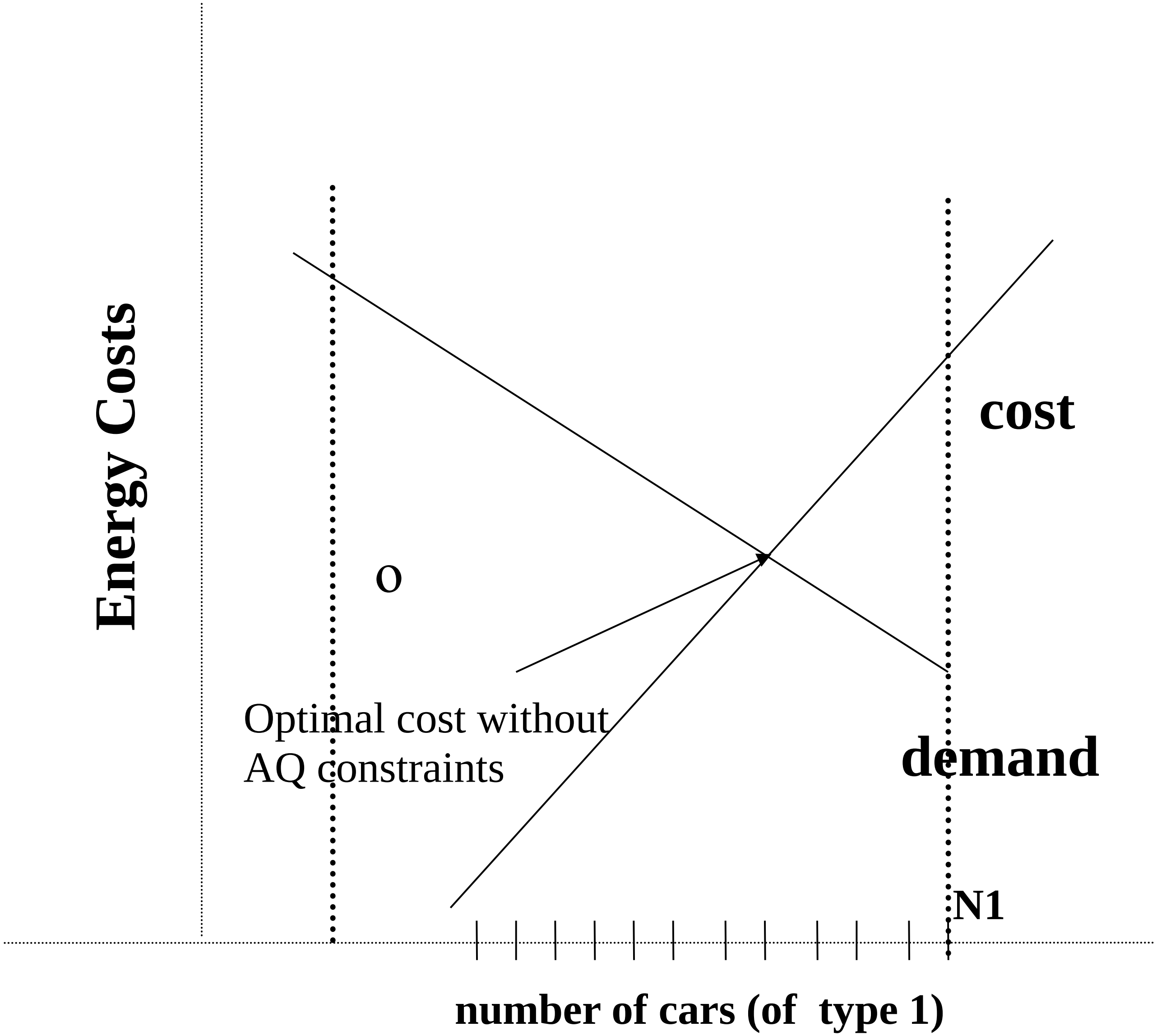


Car – type 1



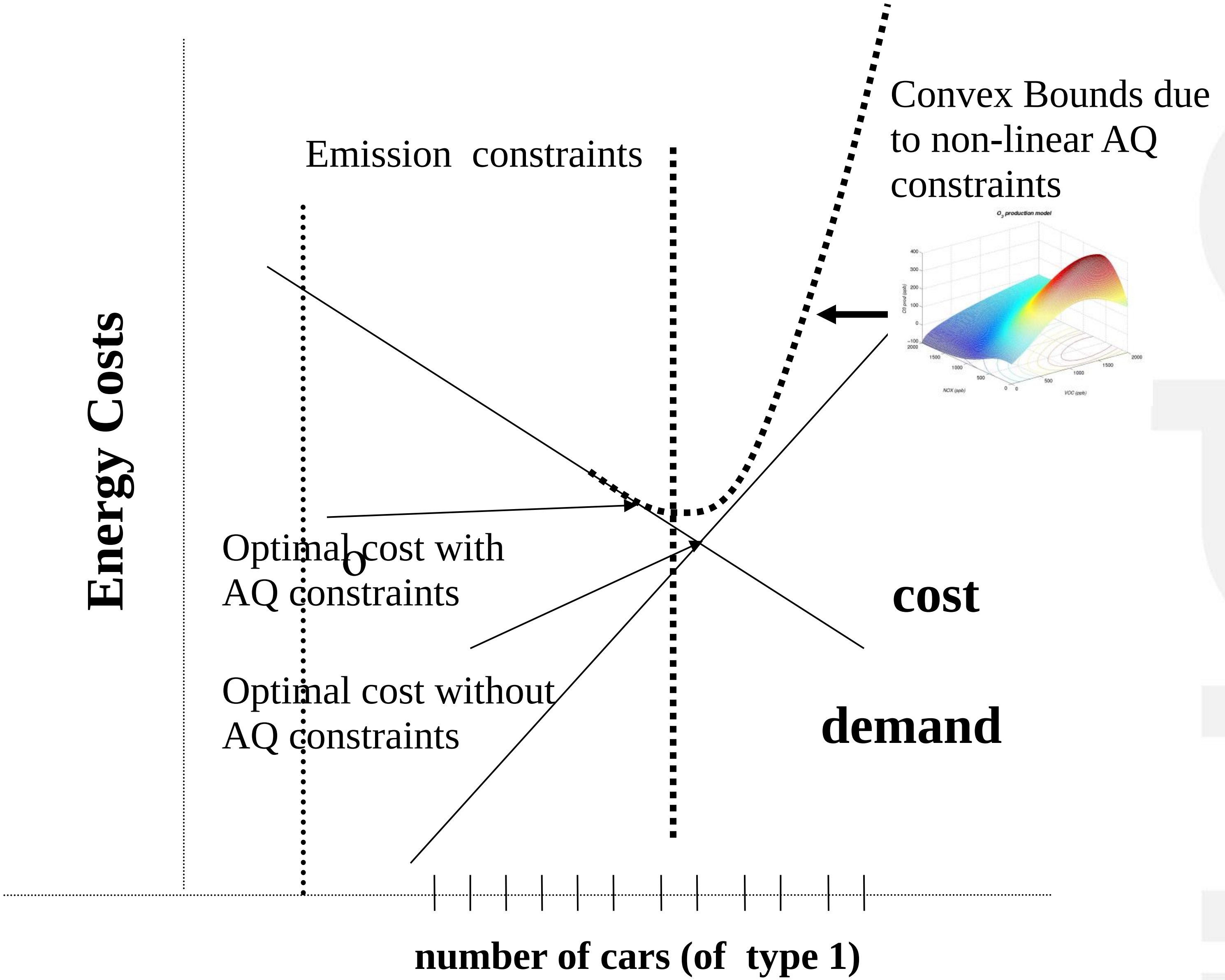
Car – type 2

A short overview of convex optimization



Optimal cost without AQ constraints

A short overview of convex optimization



Convex Bounds due
to non-linear AQ
constraints

Emission constraints

Energy Costs

Optimal cost with
AQ constraints

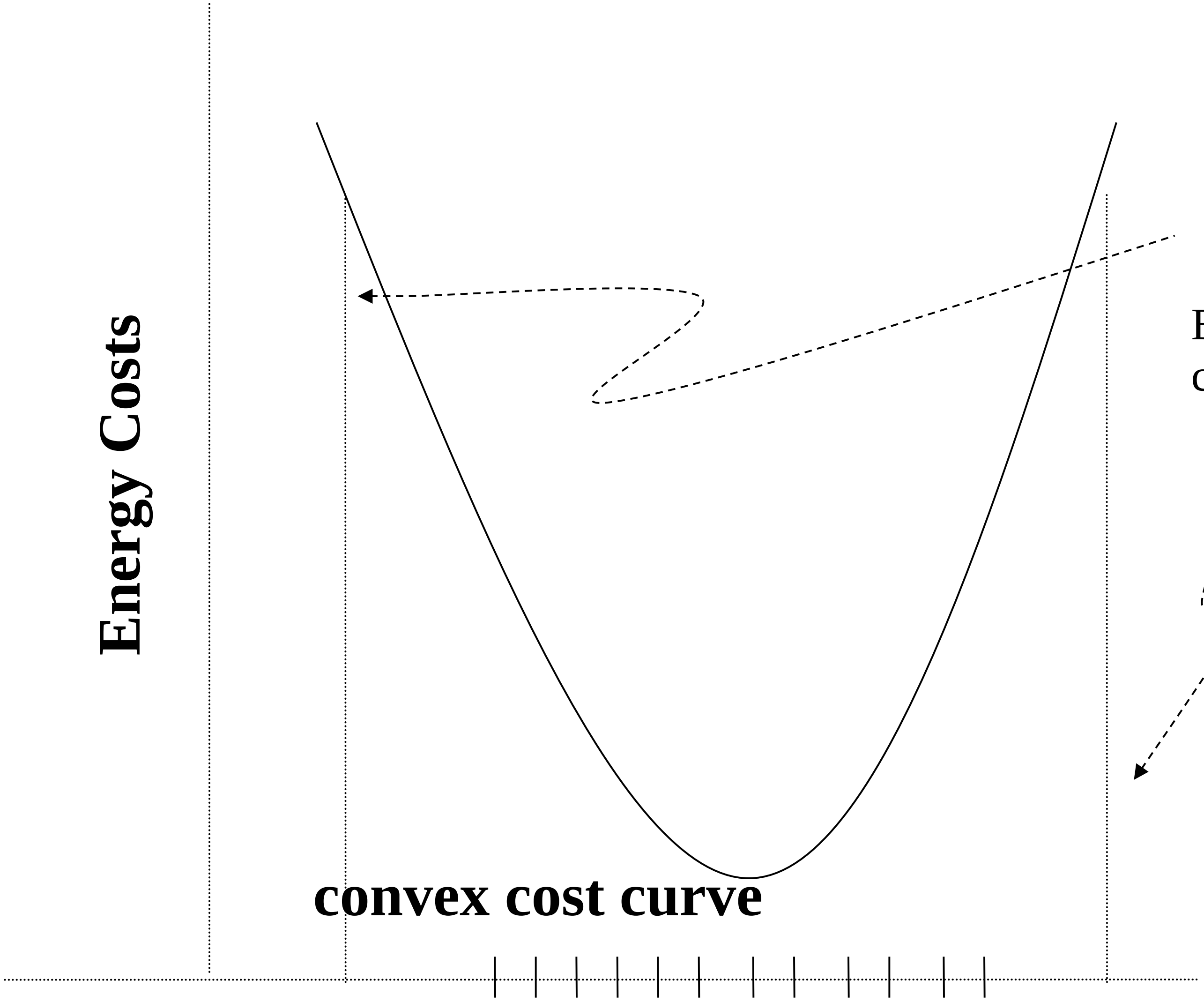
Optimal cost without
AQ constraints

cost

demand

number of cars (of type 1)

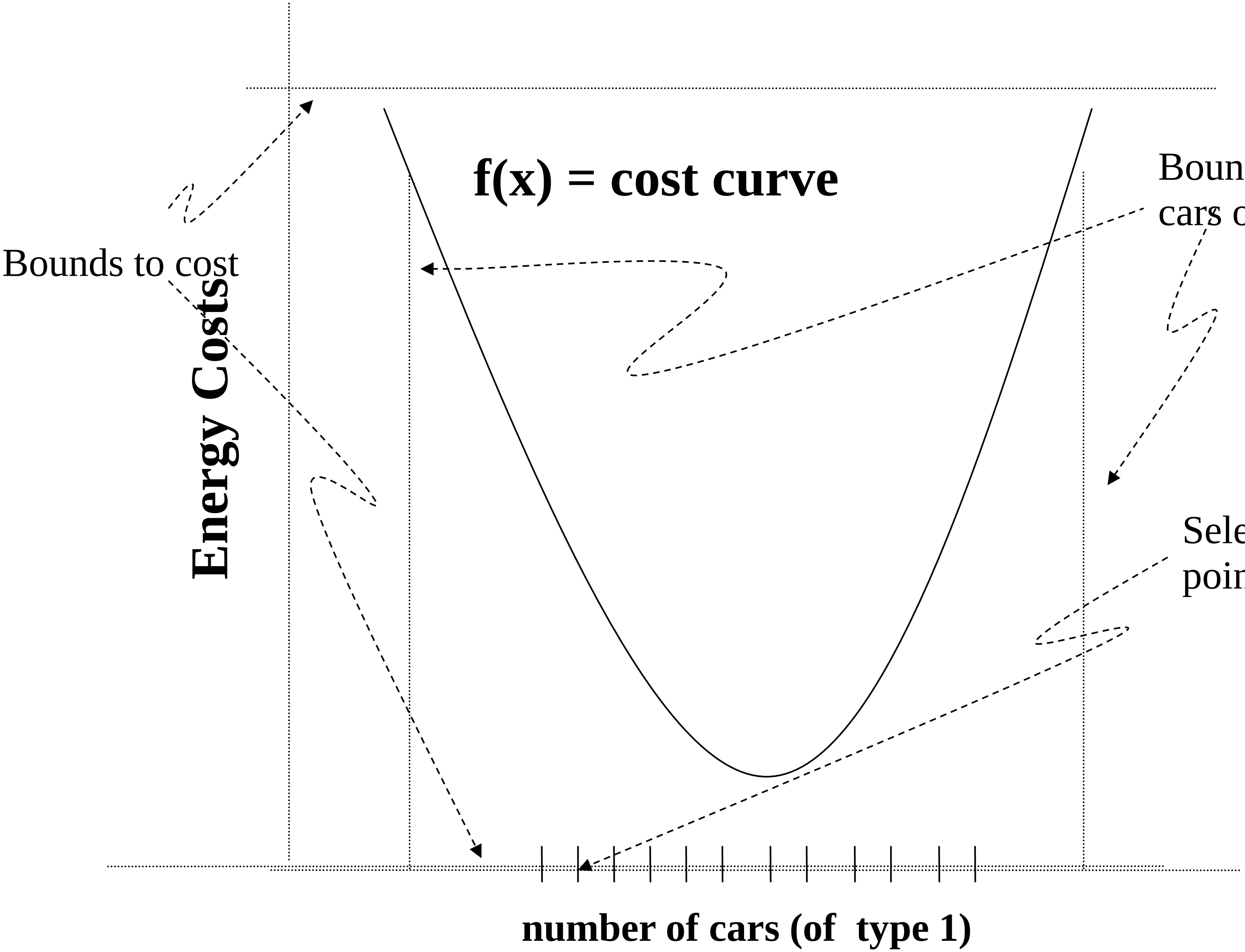
A short overview of convex optimization



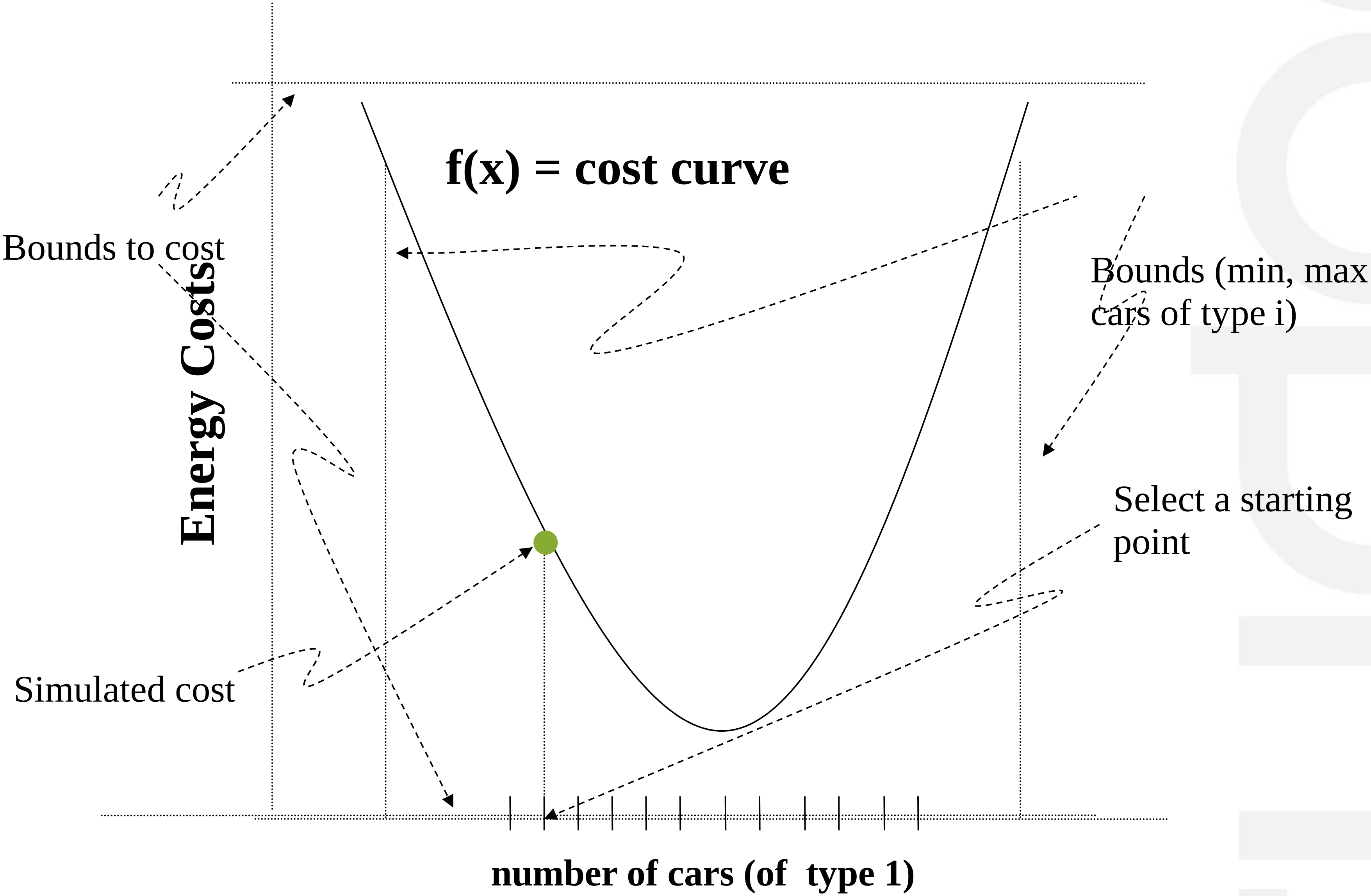
Bounds (min, max cars of type i)

number of cars (of type 1)

A short overview of convex optimization



A short overview of convex optimization



f(x) = cost curve

Bounds to cost

Energy Costs

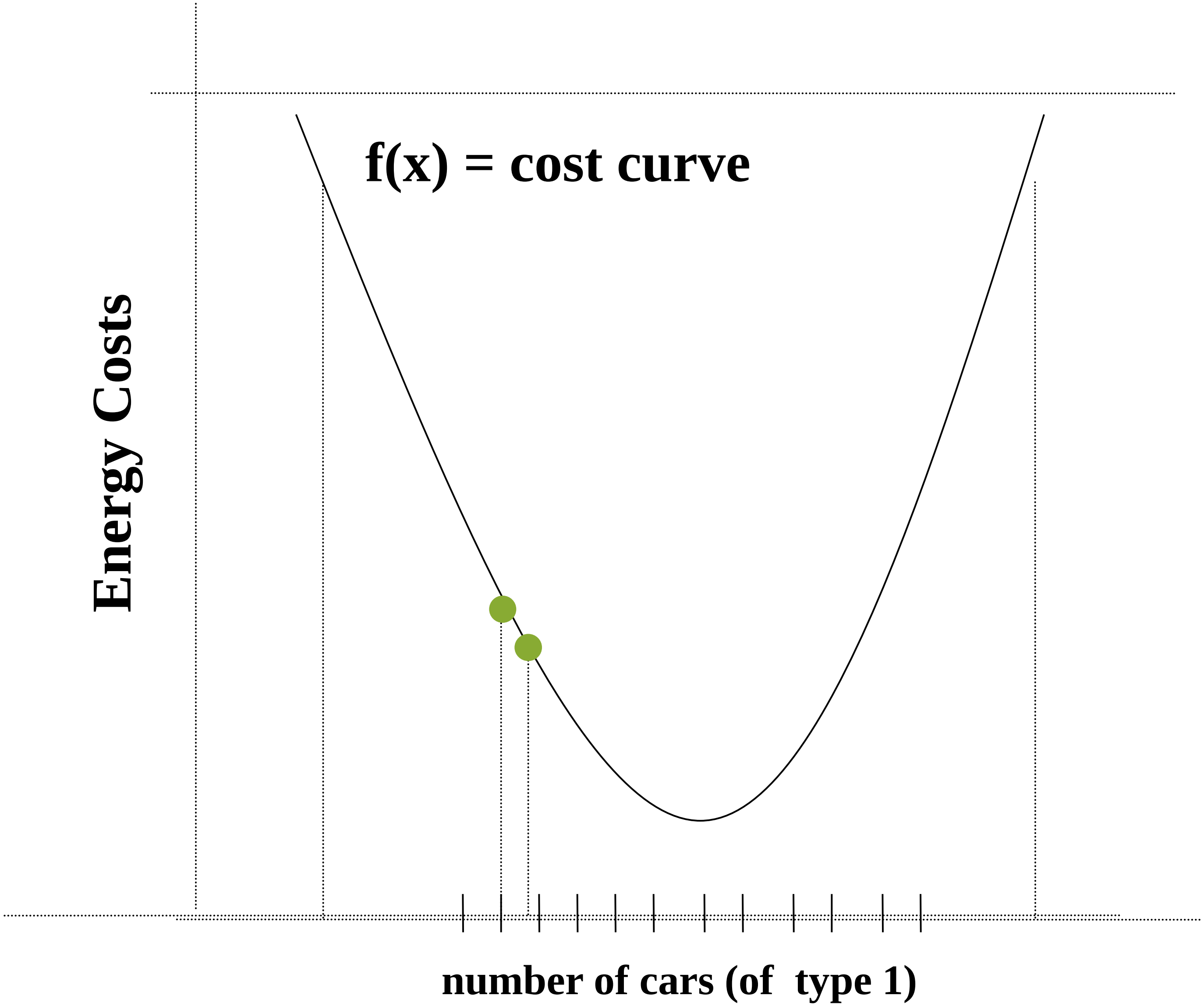
Bounds (min, max cars of type i)

Select a starting point

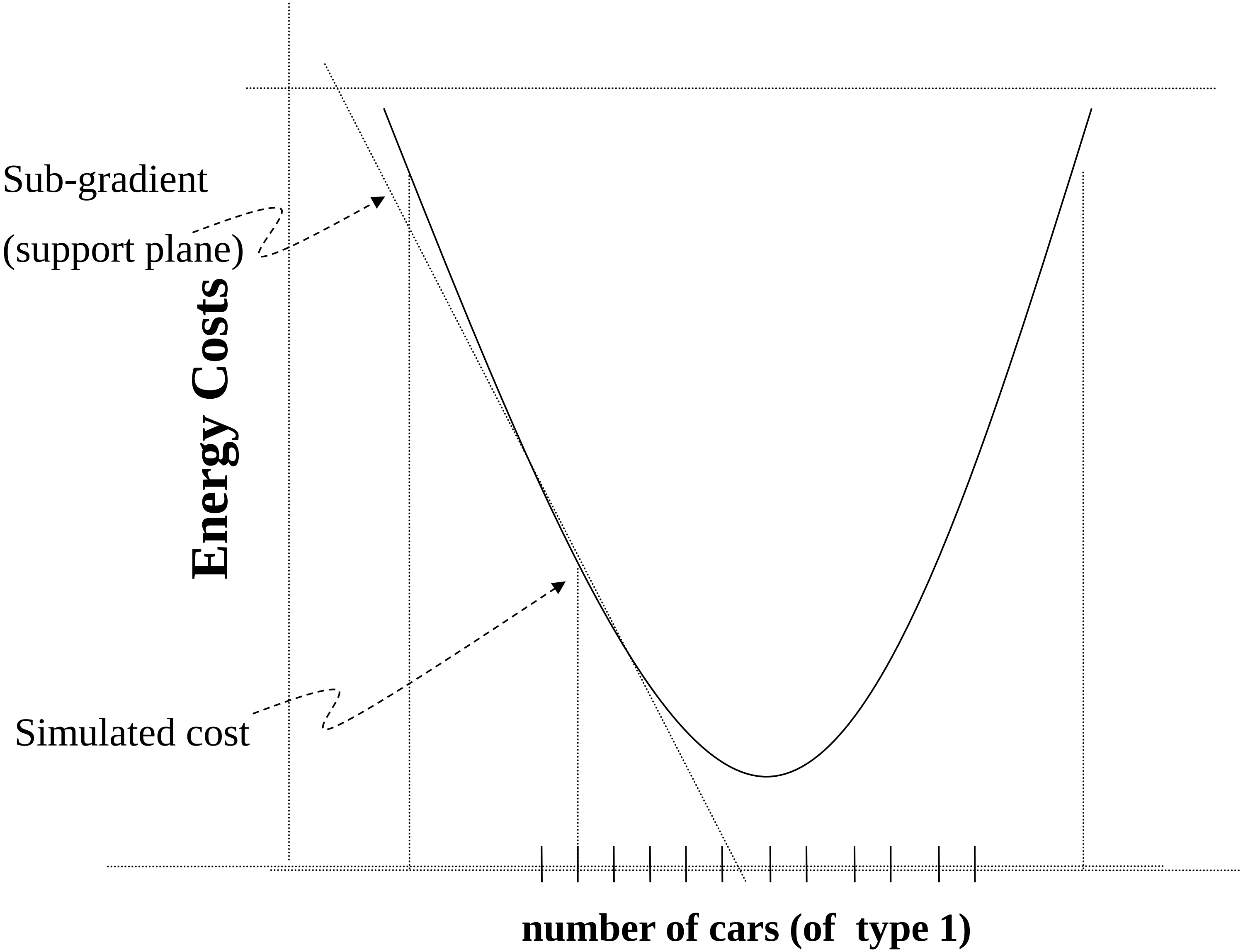
Simulated cost

number of cars (of type 1)

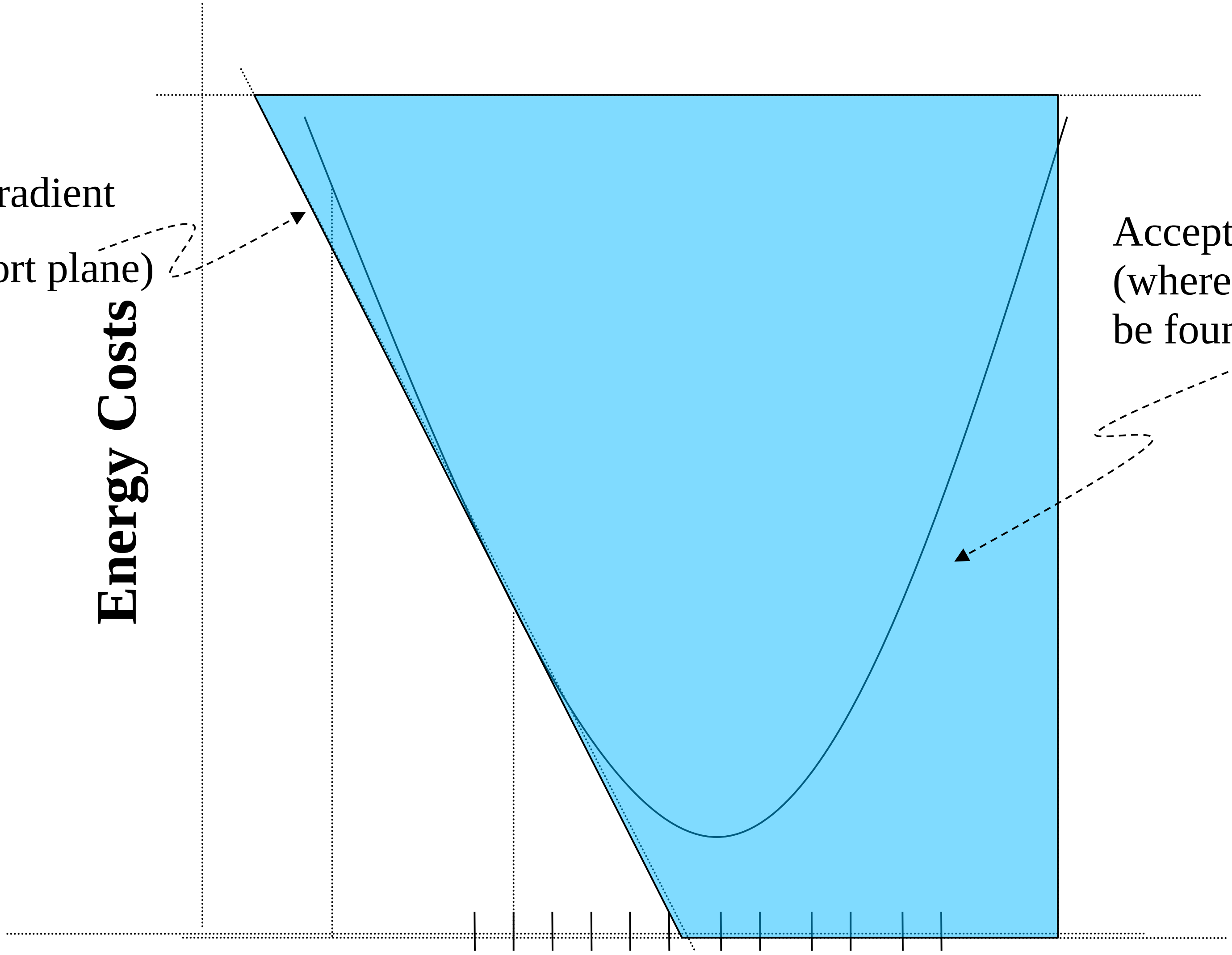
A short overview of convex optimization



A short overview of convex optimization



A short overview of convex optimization



Sub-gradient

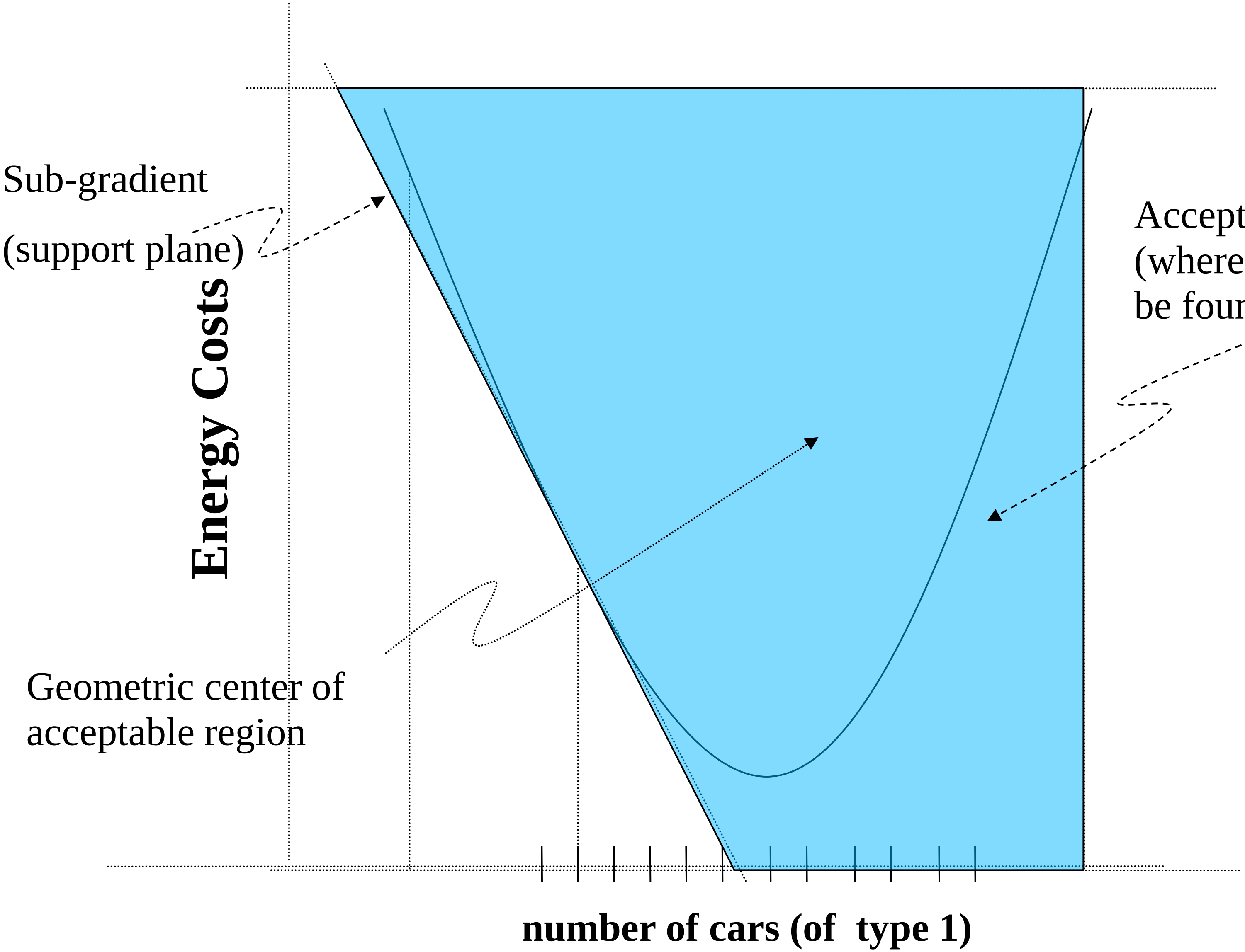
(support plane)

Energy Costs

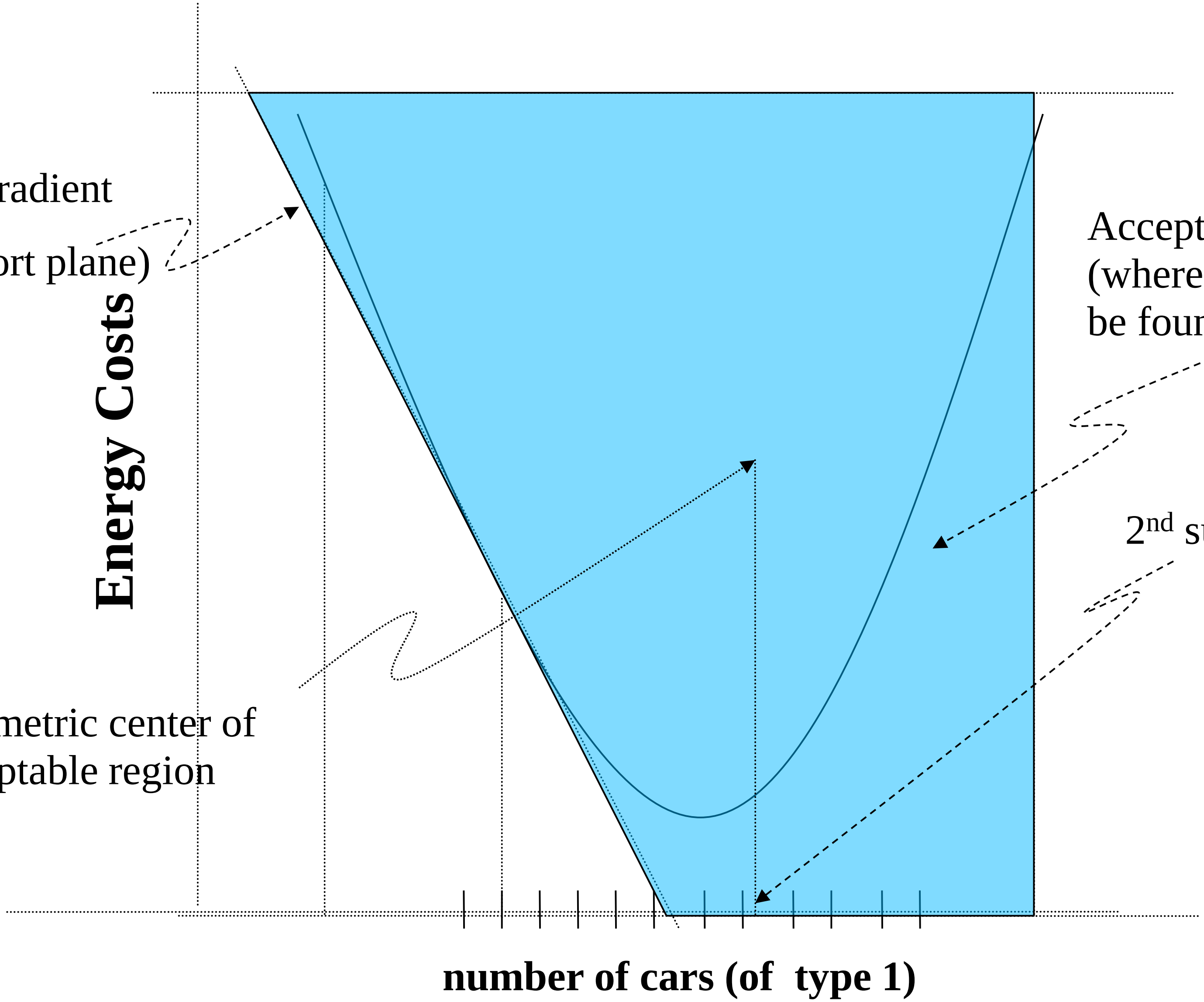
Acceptable region
(where solution must
be found)

number of cars (of type 1)

A short overview of convex optimization



A short overview of convex optimization



Sub-gradient

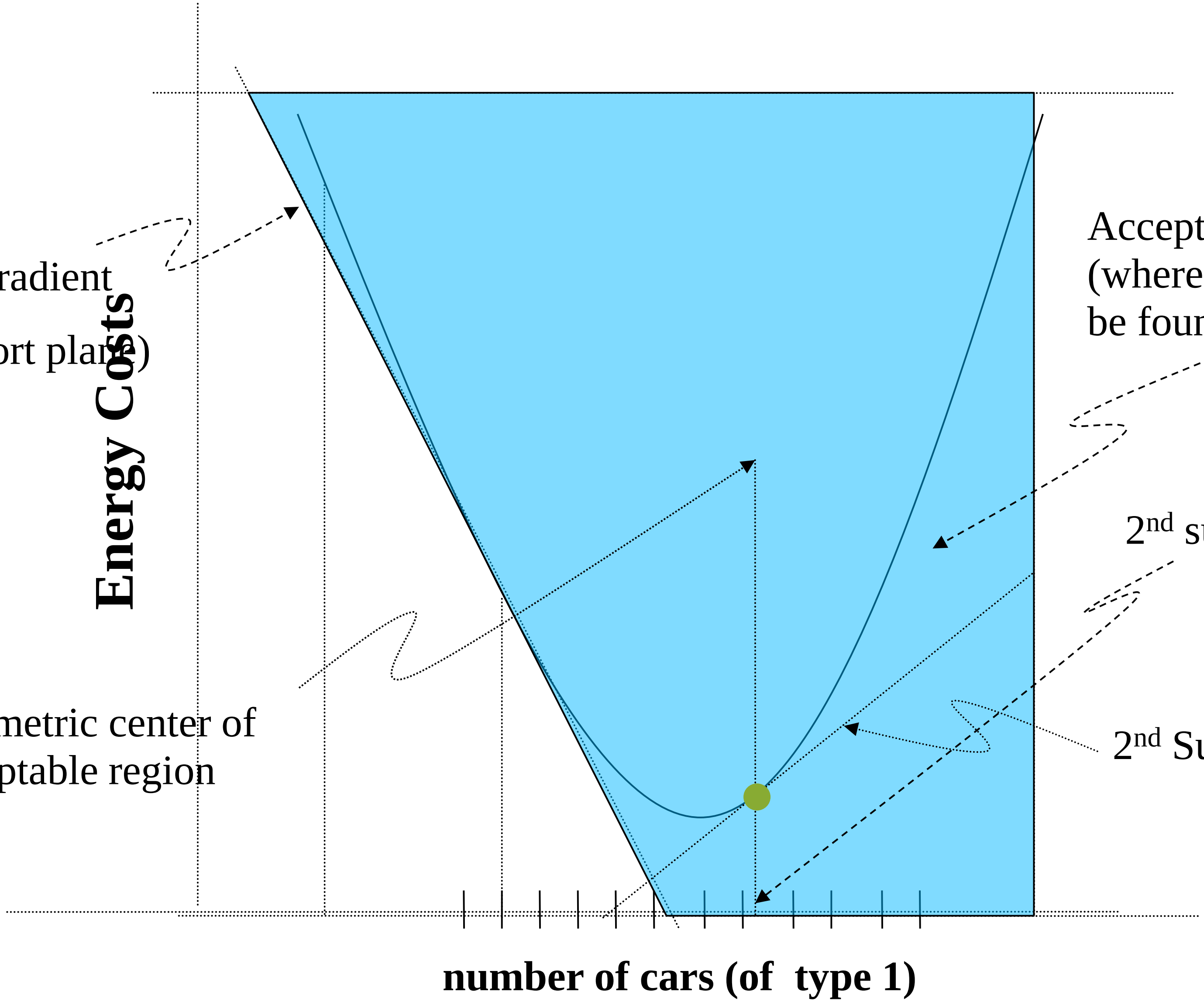
(support plane)

Acceptable region (where solution must be found)

2nd suggested point

Geometric center of acceptable region

A short overview of convex optimization



Sub-gradient

(support plane)

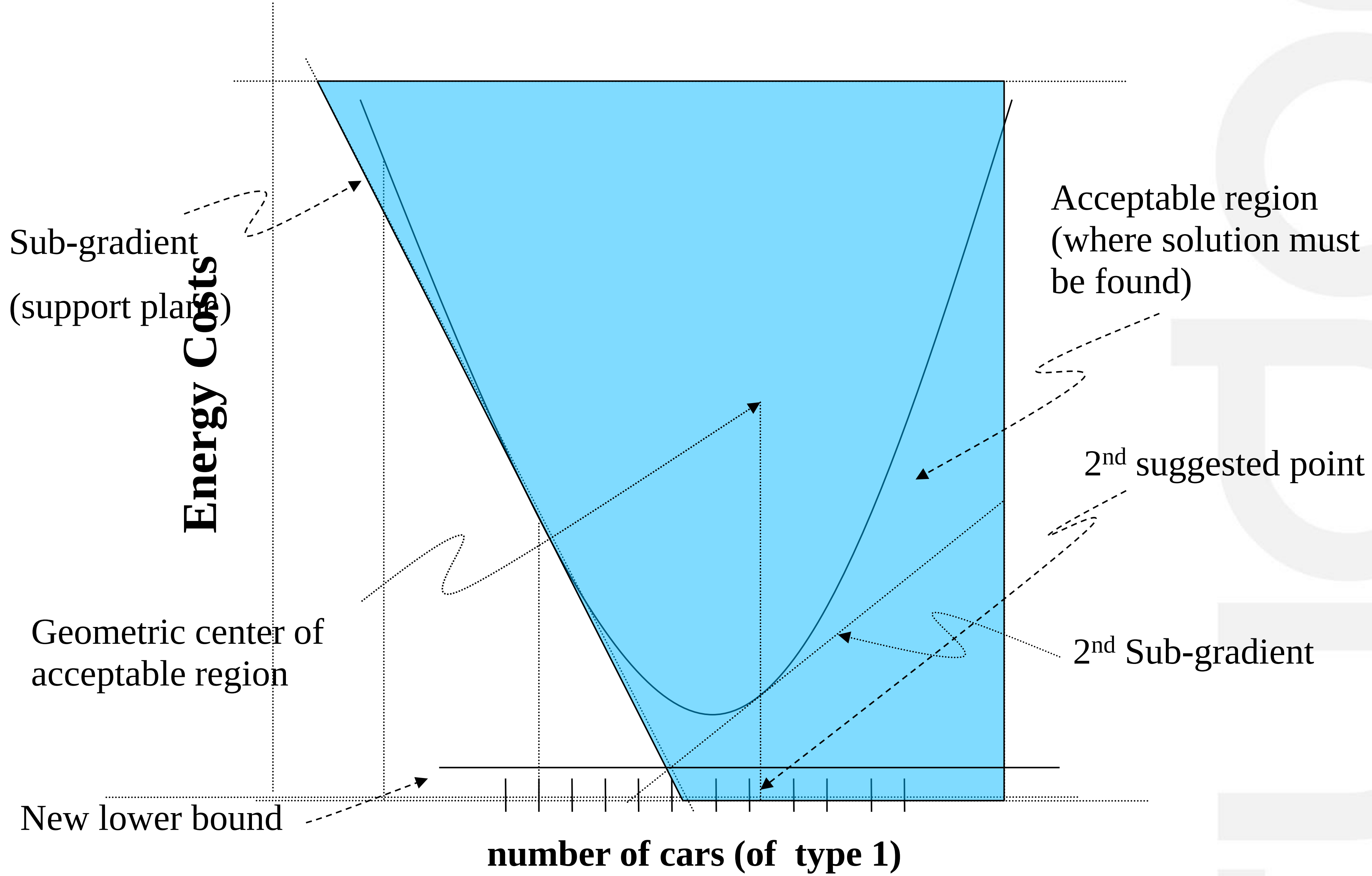
Acceptable region (where solution must be found)

2nd suggested point

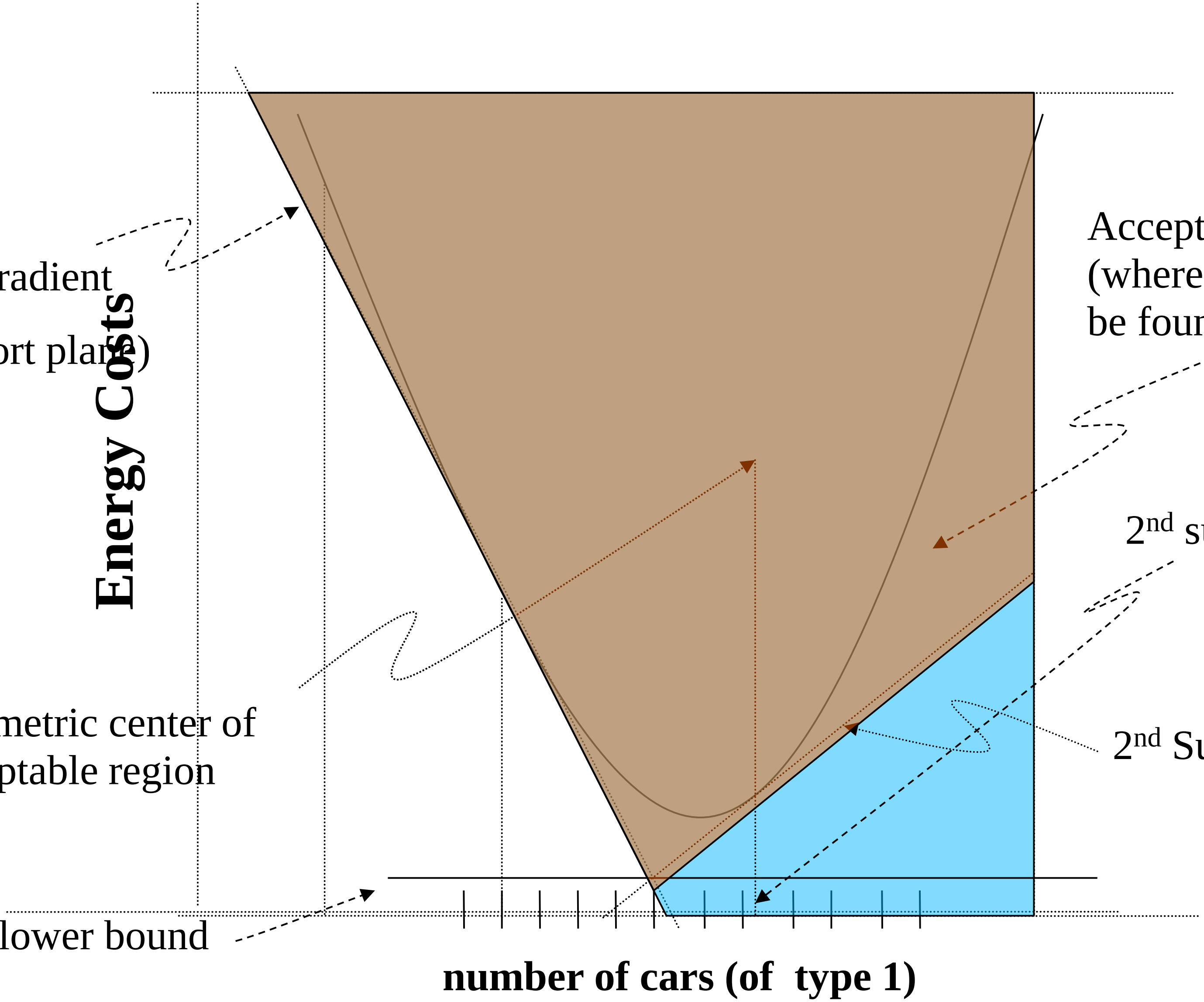
2nd Sub-gradient

Geometric center of acceptable region

A short overview of convex optimization



A short overview of convex optimization



Sub-gradient

(support plane)

Energy Costs

Acceptable region
(where solution must
be found)

2nd suggested point

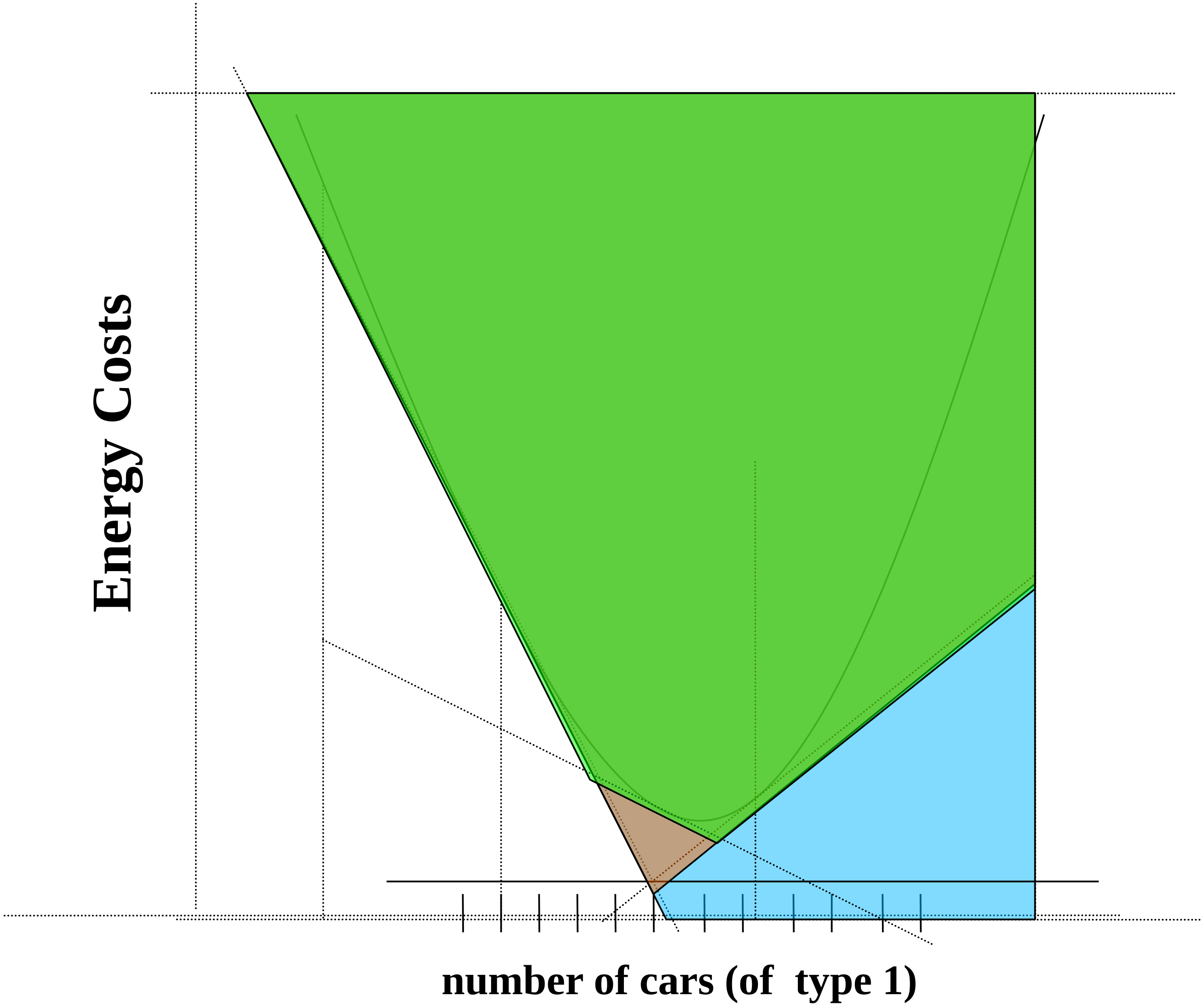
Geometric center of
acceptable region

2nd Sub-gradient

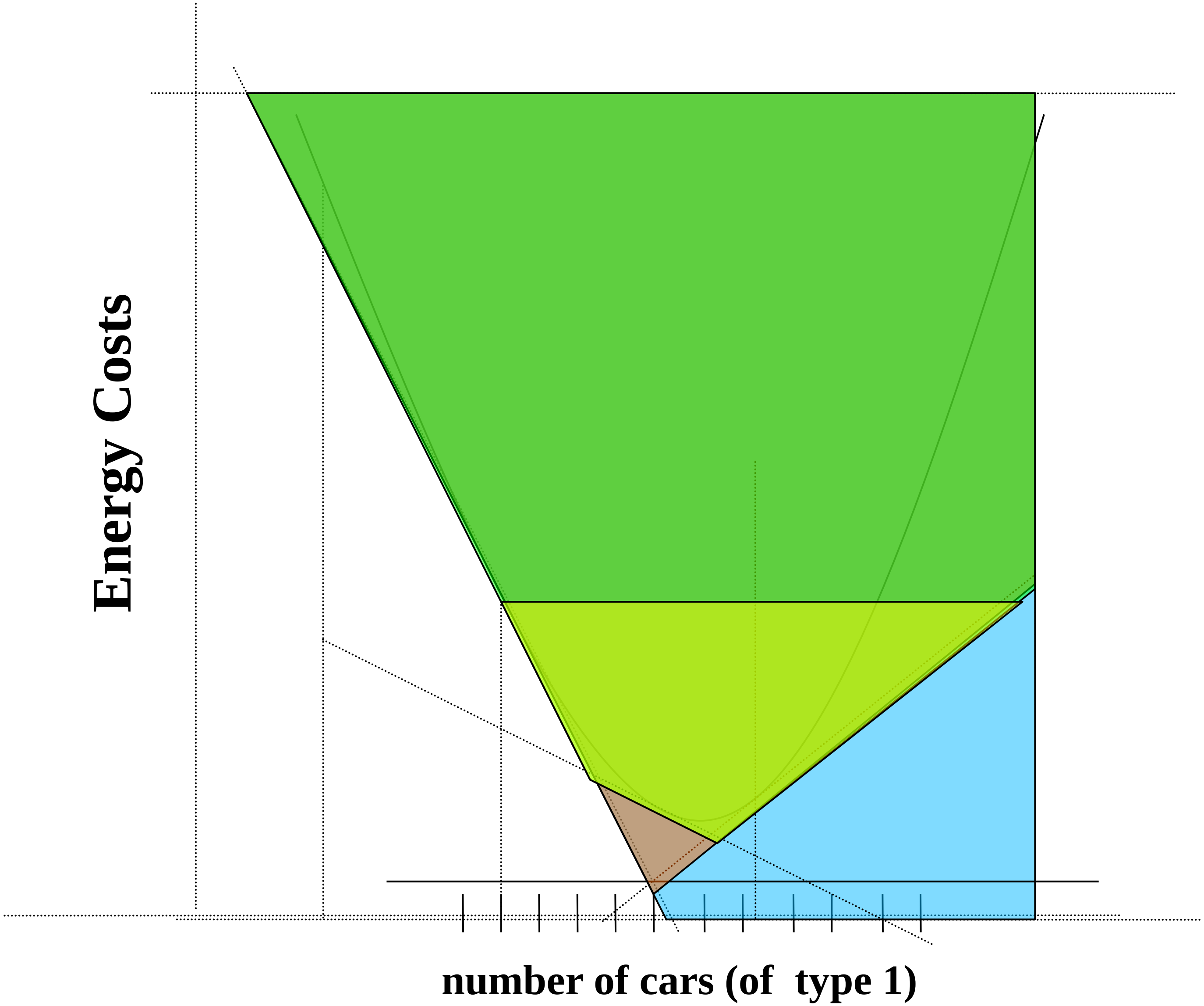
New lower bound

number of cars (of type 1)

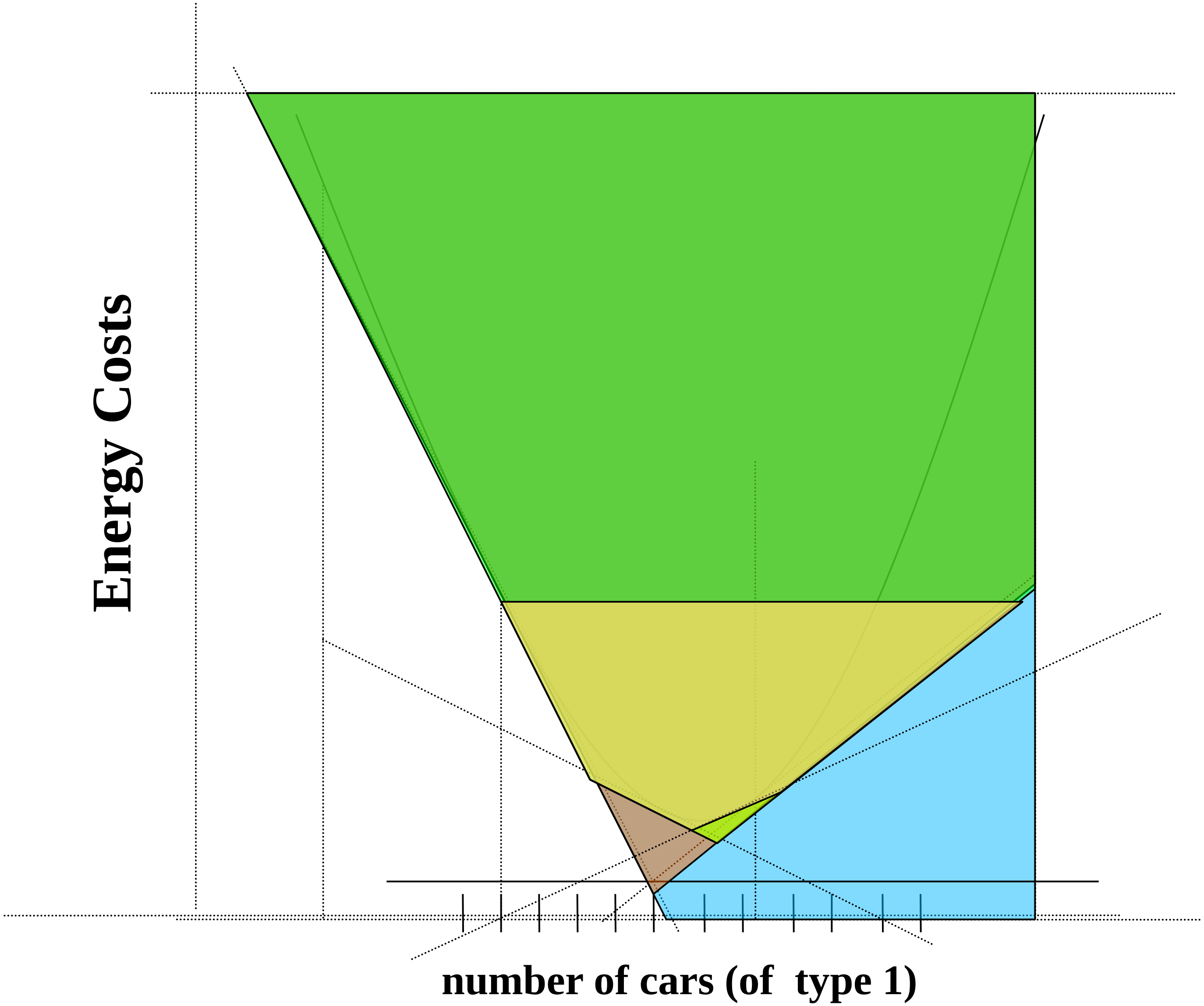
A short overview of convex optimization



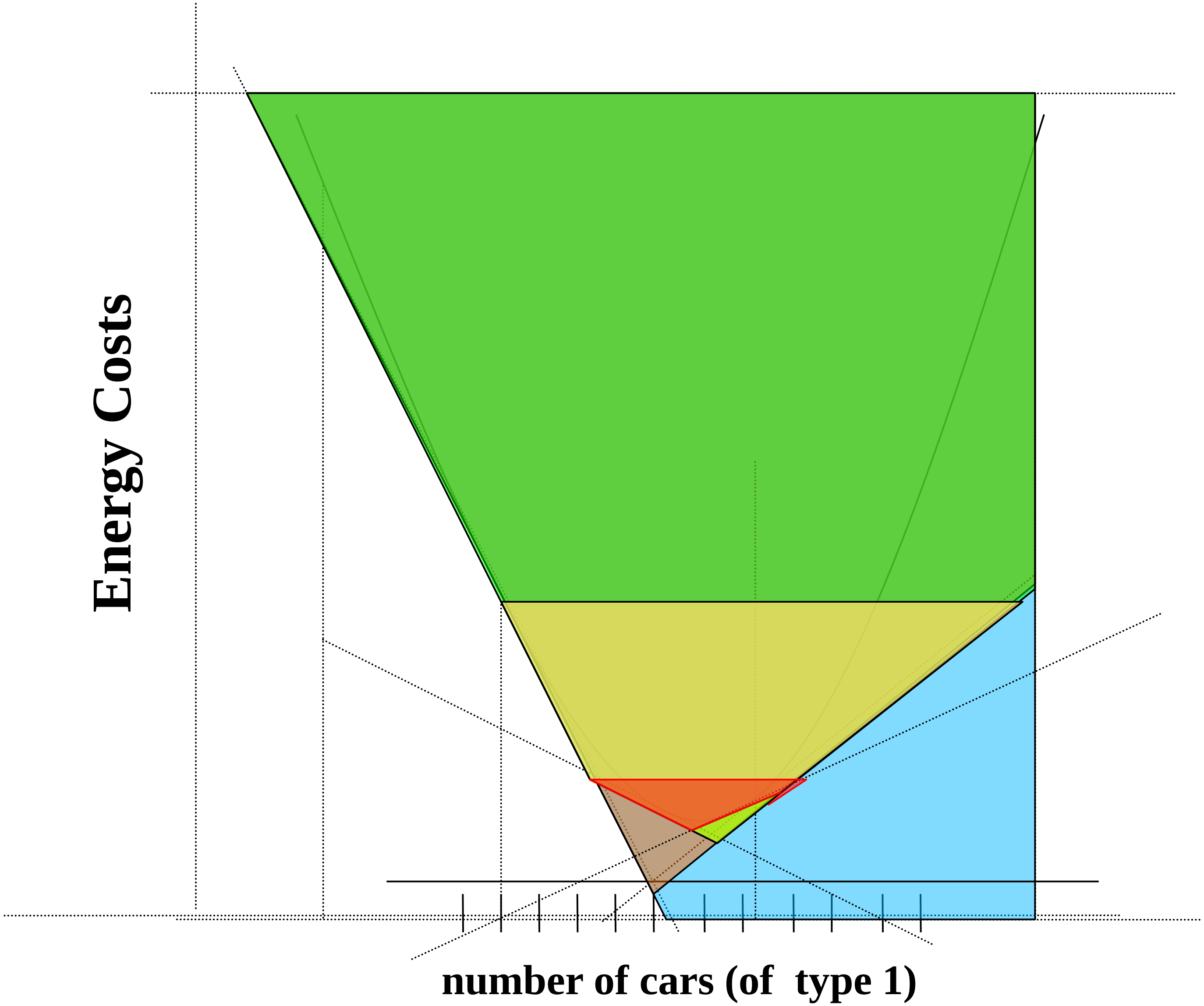
A short overview of convex optimization



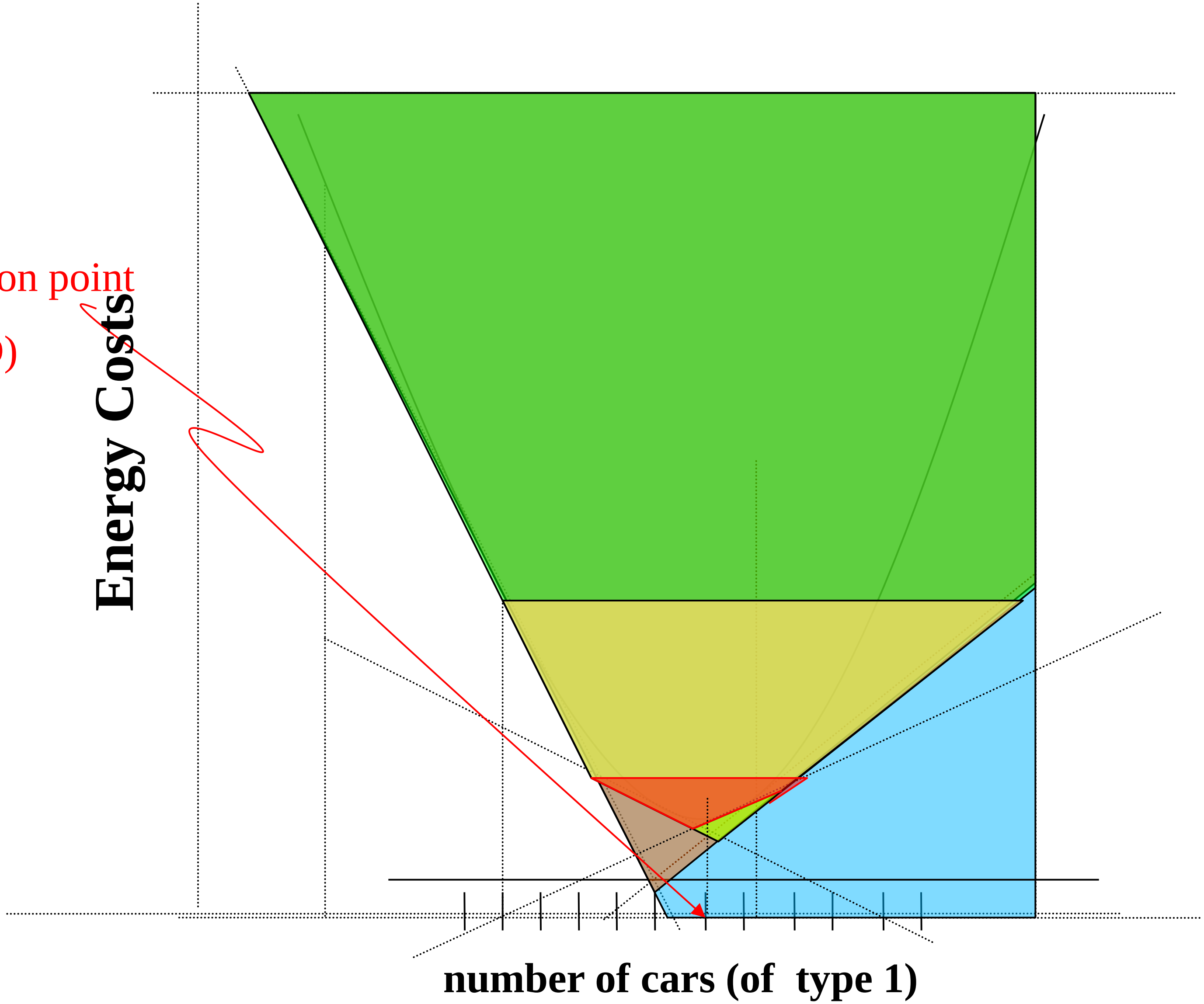
A short overview of convex optimization



A short overview of convex optimization



A short overview of convex optimization



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Results

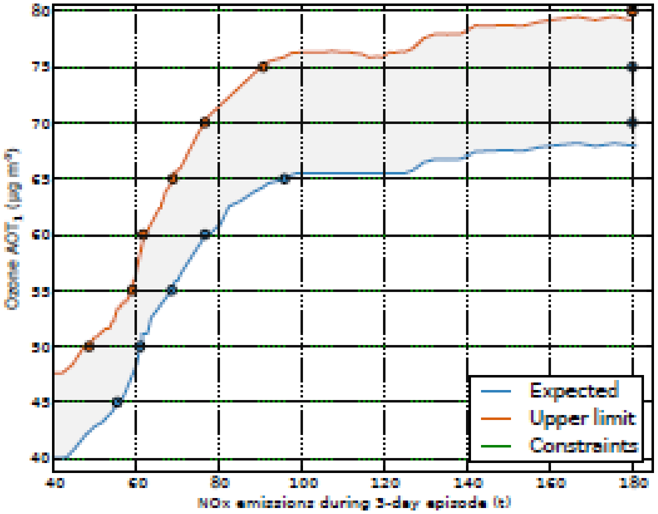
Three results

1) Emissions & Air quality management
2) Public health & planning
3) Energy policy

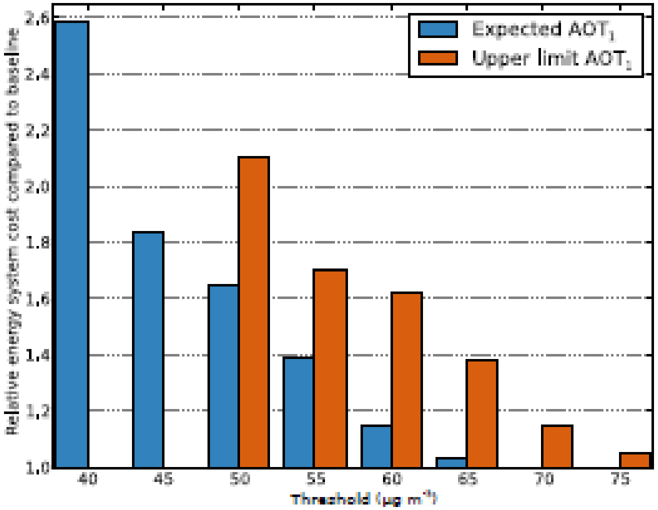
Results - e.g. Luxembourg (Scenario 1)

The Luxembourg Country:

- Scenario 1: NO_x national emissions.
- Uncertainty of the air quality model, using 95% of the upper limit of the confidence interval.



Optimal emissions vs AOT_1-indicator

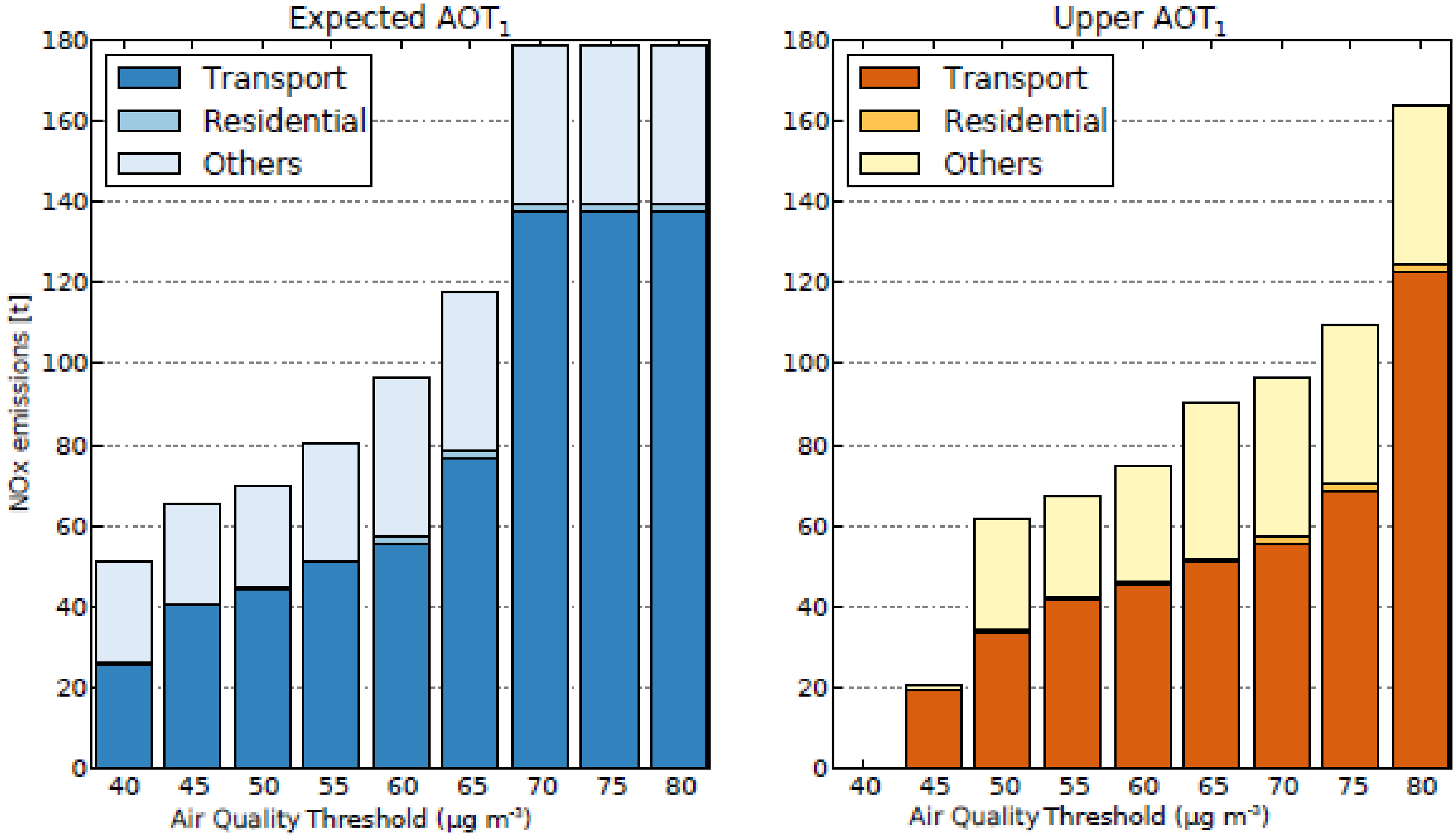


Relative cost vs AOT_1-indicator

Results - e.g. Luxembourg (Scenario 2)

The Luxembourg Country:

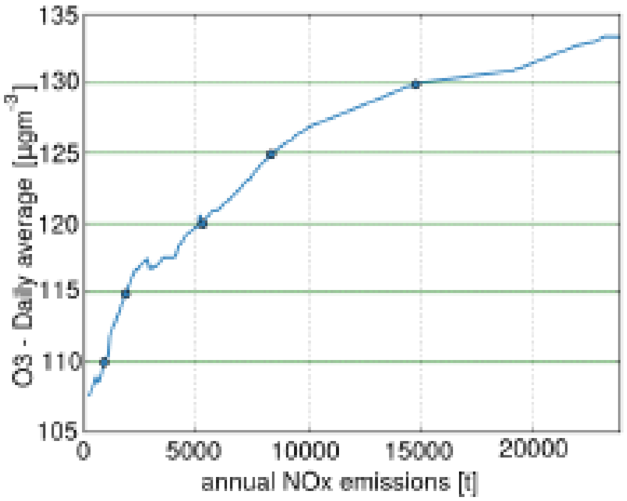
- Scenario 2: NO_x sectoral emissions.



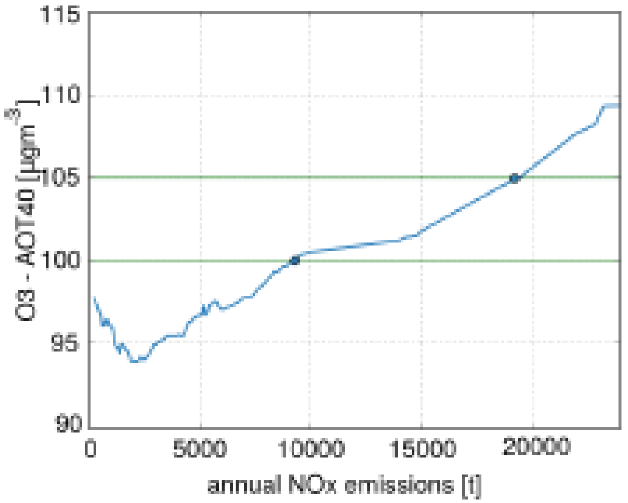
Results - e.g. Luxembourg region

The Luxembourg Region:

- NO_x national emissions.



Daily average



AOT_{40}

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Thank you

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Zachary D.S., Drouet L., Leopold U., Reis L.A. Trade-offs Between Energy Cost and Health Impact in a Regional Coupled Energy-Air Quality Model, Environmental Research Letters, 6(201), doi:10.1088/1748-9326/6/2/024021, 2011.

2) Public health and planning

Zachary D.S., Drouet L., Leopold U., Reis L.A. , Environmental Research Letters, 6(201), 2011.

$\mathrm{Min}\{\gamma(\varepsilon)\cdot I(\rho): p(\varepsilon) - \rho\} \leq 0$

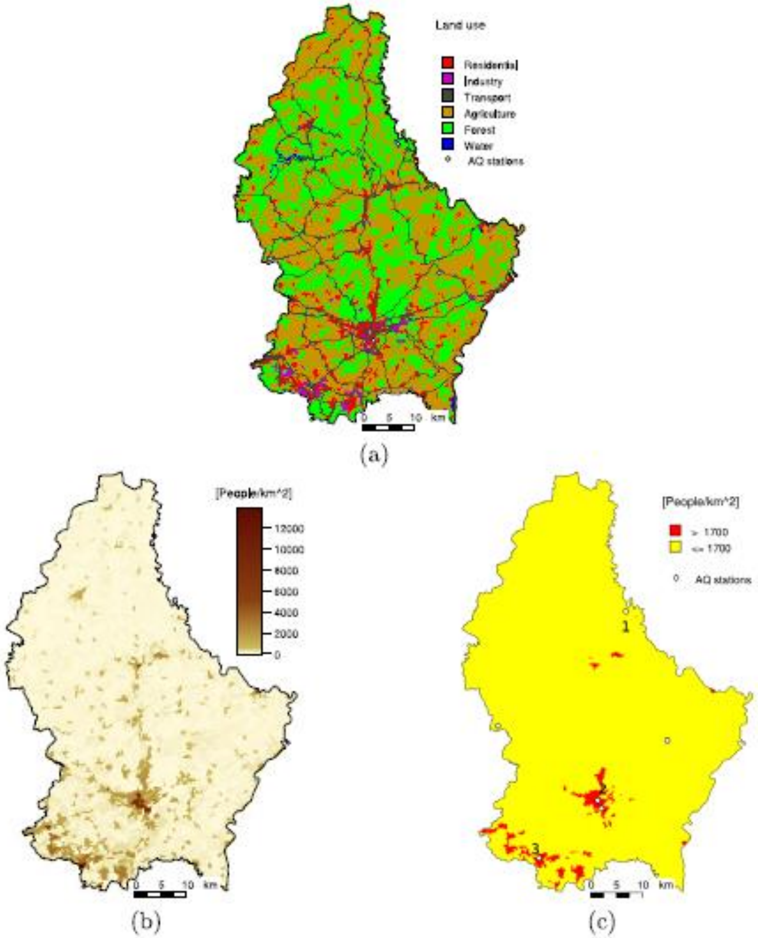
ε = emission (tons per year) (decision variable)

γ = total discounted energy costs

I = impact function (ozone - health)

p = ozone concentration (ppb)

ρ = average ozone concentration (ppb) (decision variable



With Impact considerations

Without Impact considerations

	ETEM only		Coupled model					
			$h = 1$		$h = 3$		$h = 5$	
Periods	2	3	2	3	2	3	2	3
NO_x (kt yr^{-1})	15 617	15 618	13 962	14 389	13 372	13 797	12 714	13104
VOC (kt yr^{-1})	6702	6703	2901	3006	322	333	322	333