Optimisation tools for *green*ing road freight transport

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LAAS-CNRS
Toulouse, September 2017

Why Go Green in Freight Transport?

European Environment Agency, TERM 2013:

- The EC White Paper on transport: 60% reduction target in GHG emissions from transport by 2050 compared to 1990 levels.
- Overall GHG emissions from transport have reduced by 0.6% in 2011.
- They are still 25% above the 1990 levels.
- Road continues to be the dominating mode (76% of total inland freight movements within the EU-28).


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20
ZONE

Freight Transport Planning

- Existing work on minimizing "internal" costs
- Need explicit consideration of "external" (environmental) costs, in particular CO_2
- Build external costs into freight distribution planning for "better" plans

Disclaimer

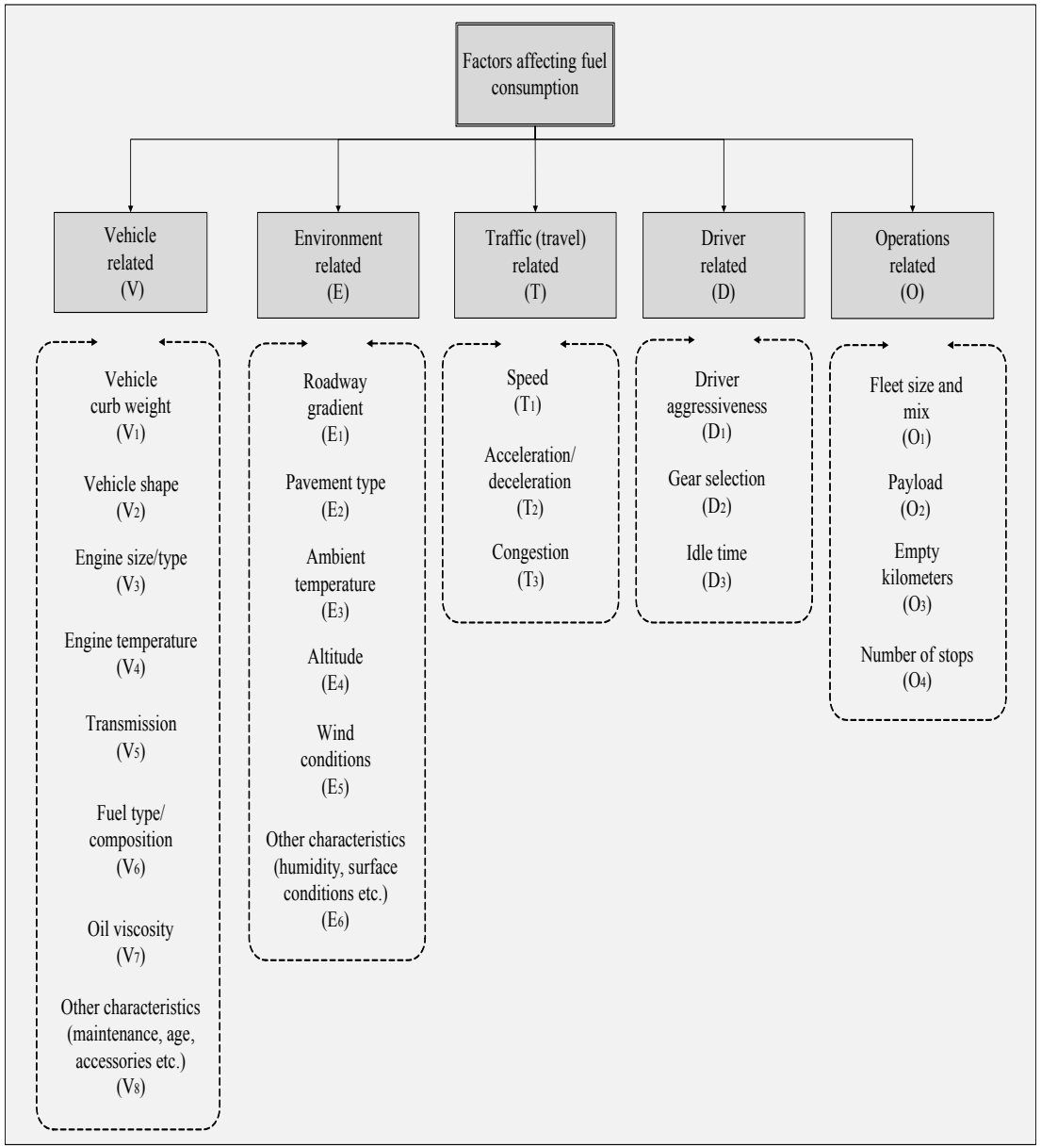
This talk is NOT about:

1. Green Supply Chains
2. Electric Vehicles
3. "Sustainability"
4. Passenger Transportation
5. A Survey of Green Logistics

Part I

Emissions Modelling

Factors affecting emissions



Estimating emissions

There are a number of emission estimation models in the literature:

- Macroscopic (average speed) models, generally used for wide-area emissions assessment (supply chains, etc.)
- Microscopic (instantaneous) models for hot-stabilised vehicle emissions, based on kinematic variables such as speed and aggregation

Ranging from simple...

Everall (1968):

$$F = 0.0047(20E^{0.52})(1 + 40/v) + 0.0047M.$$

F is the total fuel consumption (in L per 100 km), M denotes the load and E is the engine displacement.

...to somewhat complex...

COPERT (2000):

Weight Class	Speed Range	Emission Factor [g/km]
Weight <3.5	10–120	$0.0198v^2 - 2.506v + 137.42$
$3.5 <$ Weight <16	0–47	$1425.2v^{-0.7593}$
$3.5 <$ Weight <16	47–110	$0.0082v^2 - 0.0430v + 60.12$
$7.5 <$ Weight <16	0–59	$1068.4v^{-0.4905}$
$7.5 <$ Weight <16	59–110	$0.0126v^2 - 0.06589v + 141.18$
$16 <$ Weight <32	0–59	$1595.1v^{-0.4744}$
$16 <$ Weight <32	59–110	$0.0382v^2 - 5.1630v + 399.3$
Weight >32	0–58	$1855.7v^{-0.4367}$
Weight >32	58–110	$0.0765v^2 - 11.414v + 720.9$

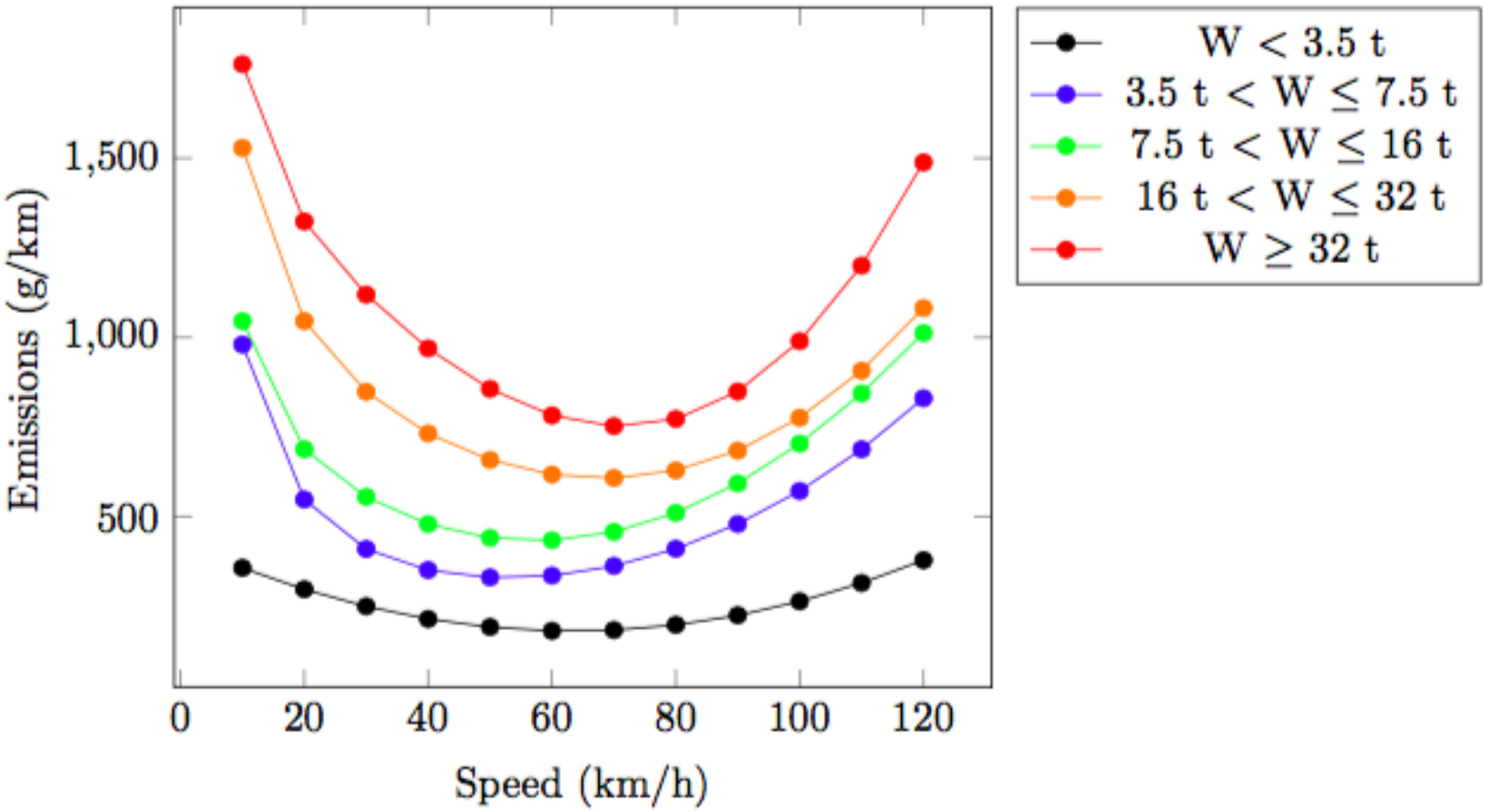
to moderately complex...

The *macroscopic* MEET (1999) model:

$$\epsilon = K + av + bv^2 + cv^3 + d/v + e/v^2 + f/v^3,$$

- ϵ is the rate of emissions (g/km) for an unloaded goods vehicle on a road with a zero gradient, v is the average speed of the vehicle (km/h).
- K and a–f are predefined coefficients for different classes of vehicles.

Emission curves with the MEET model



...to *very* complex

Part of the four-mode *microscopic* model by Bowyer et al. (1985):

$$F_a = \max\{\alpha t_a + [A + k_1 B(v_i^2 + v_f^2) + \beta_1 M E_k + k_2 \beta_2 M E_k^2 + 0.0981 \beta_1 M \omega] x_a, \alpha t_a\}.$$

- E_k: change in kinetic energy per unit distance during acceleration and integration coefficients
- $E_k = 0.3858\,10^{-4}(v_f^2 - v_i^2)/x_a$
- $k_1 = 0.616 + 0.000544 v_f - 0.0171\sqrt{v_i}$
- $k_2 = 1.376 + 0.00205 v_f - 0.00538 v_i$
- Estimated travel distance $x_a = m_a(v_i + v_f)t_a/3600$ with $m_a = 0.467 + 0.00200 v_f - 0.00210 v_i$
- Estimated travel time $t_a = (v_f - v_i)/(2.08 + 0.127\sqrt{v_f - v_i} - 0.0182 v_i)$

Estimating emissions

CMEM by Barth *et al.* (2005):

Emission rate E (grams/second) proportional to fuel use rate F (grams/second)

$$F \approx (kNV + (P_t/\varepsilon + P_a)/\eta)U,$$

- k is the engine friction factor,
- N is engine speed,
- V is engine displacement,
- P_t is the total tractive power demand requirement (kW),
- ε is vehicle drivetrain efficiency,
- P_a is the engine power demand associated with running losses of the engine and additional vehicle accessories (kW) such as an air conditioner,
- η is a measure of efficiency for diesel engines,
- U is a value that depends on some constants including N.

Estimating emissions

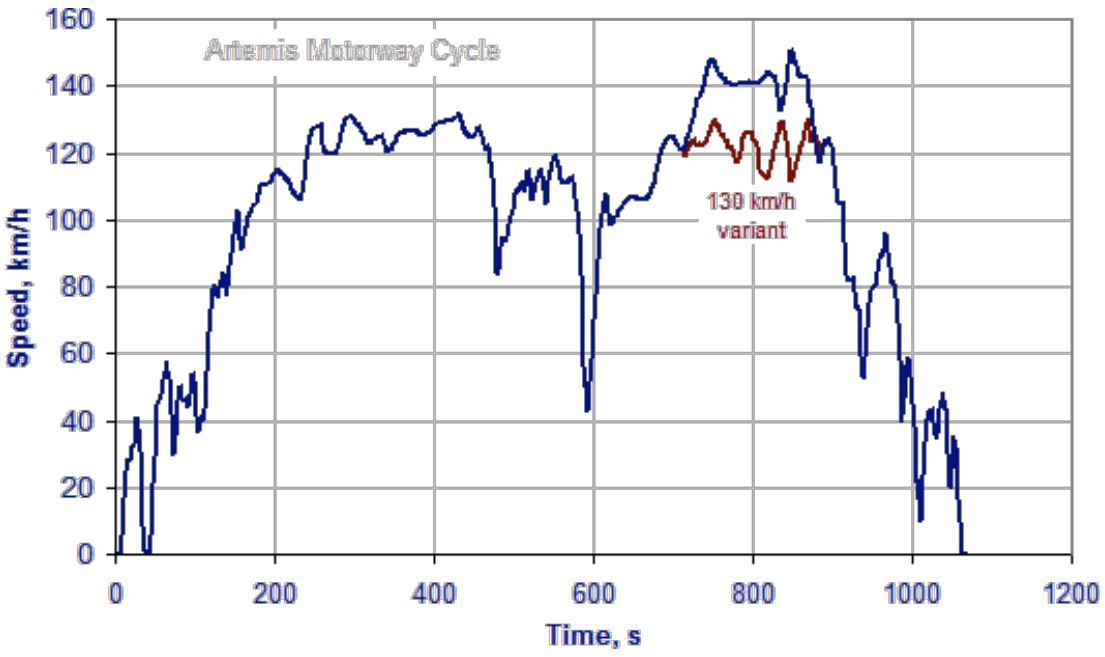
Tractive power P_t

$$P_t = (Mav + Mgvsin\theta + 0.5C_dA\rho v^3 + MgC_rcos\theta v)/1000,$$

- M is the mass (kg) of the vehicle (empty + carried load),
- v is speed (meters/second),
- a is the accelaration (meters/second^2),
- g is the gravitational constant (9.81 meters/second^2),
- θ is the road angle (degrees),
- A is the frontal surface area of the vehicle (meters^2),
- ρ is the air density (kg/meters^3),
- C_r and C_d are the coefficients of rolling resistance and drag, respectively.

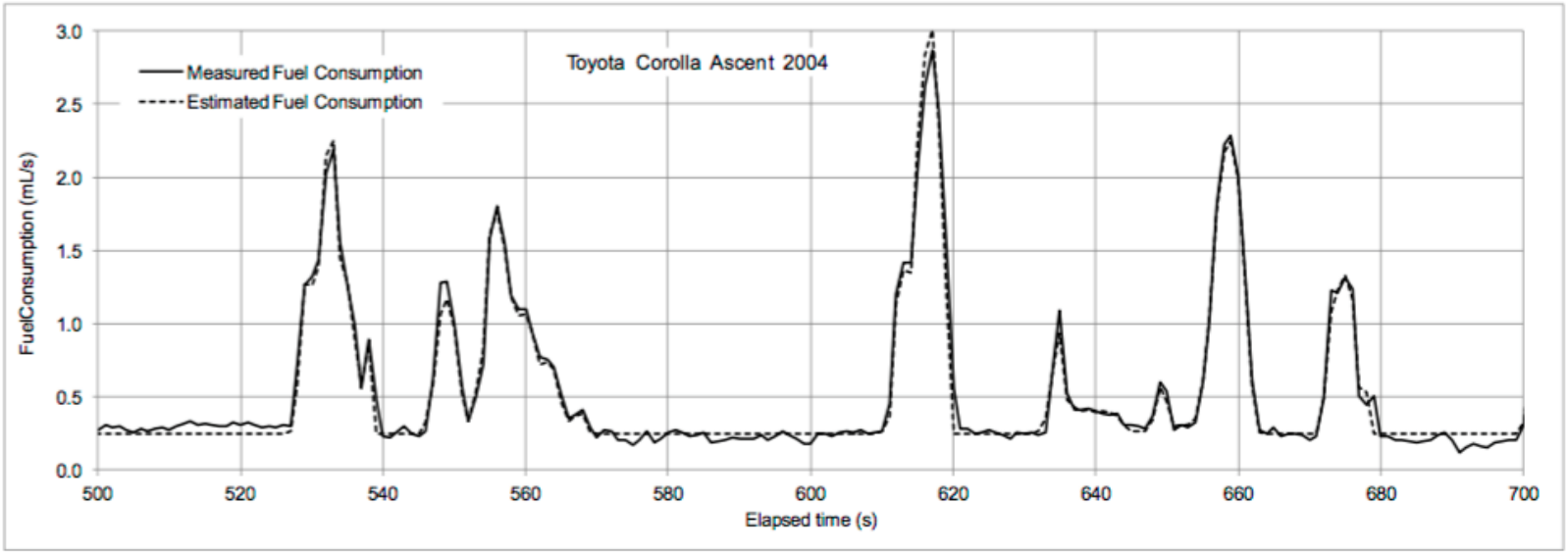
Estimating emissions

Driving cycles:



- A fixed schedule, used in emission tests to comply with the EU law
- Hundreds, if not thousands, but not without criticism: "idealised"

Accuracy



Akçelik et al. (2012), Toyota Corolla Ascent 2004

More on emission models, reviews and comparisons

- Demir, E., Bektaş, T. and Laporte, G. (2011) A comparative analysis of several vehicle emission models for freight transportation. *Transportation Research Part D: Transport and Environment* 16(5): 347–357.
- Demir, E., Bektaş, T. and Laporte, G. (2014) A review of recent research on green road freight transportation. *European Journal of Operational Research* 237(3): 775–793.
- Eglese, R. and Bektaş, T. (2014) *Green vehicle routing*. In, Toth, P. and Vigo, D. (eds.) Vehicle Routing: Problems, Methods and Applications. Berlin, DE, Springer.

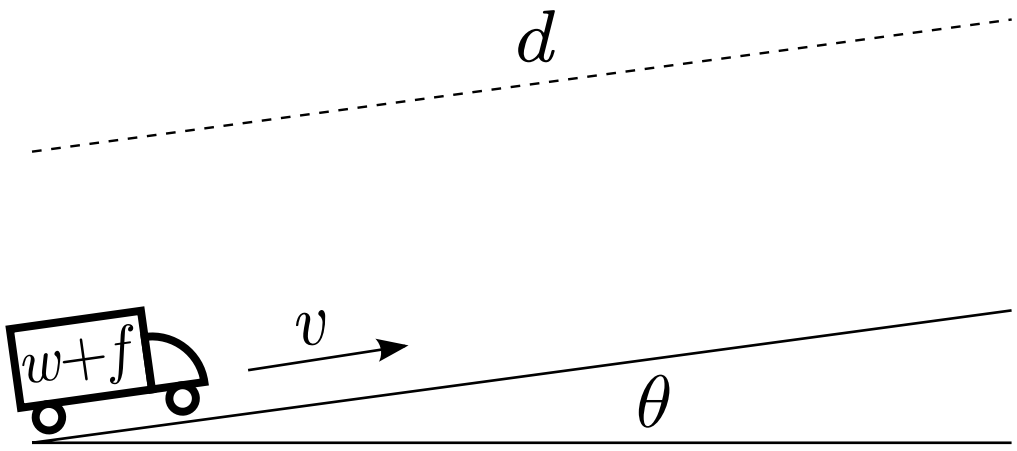
Part II

Green Routing

Vehicle Weight

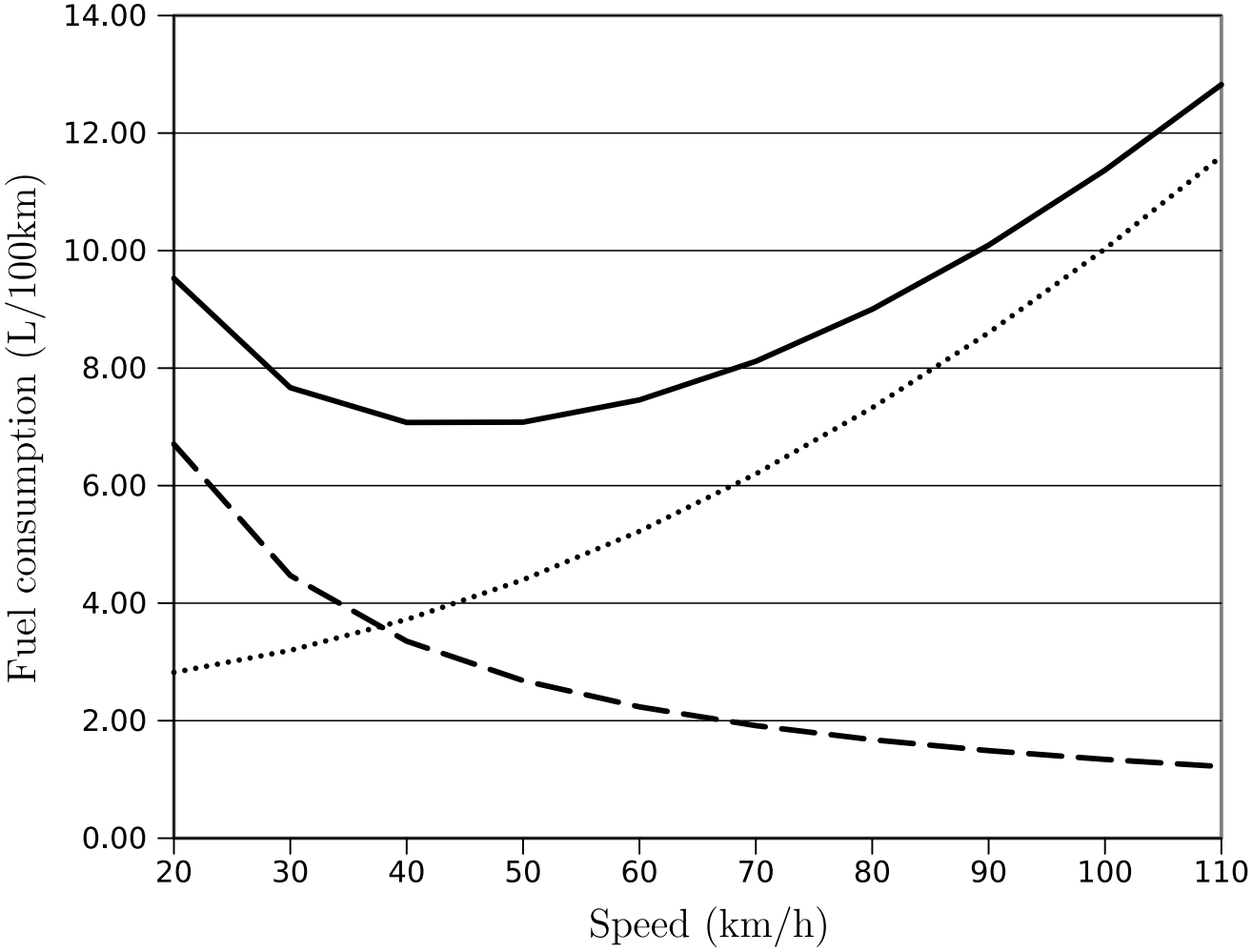
- Truck classification is usually based on *Gross Vehicle Weight Rating* (GVWR): the maximum allowable total weight of the vehicle including its empty mass, fuel and any load carried.
- The empty mass of the vehicle (but with fuel and fluids such as engine oil) is termed *curb weight*,
- Trucks are usually classified into eight classes:
  - Lightest up to around three tonnes,
  - Heaviest higher than 15 tonnes.
- We reviewed a number of different trucks to find the ratio of the curb weight of a truck to its GVWR to be between 42%–57%.

Estimating Emissions in the VRP



$$
\begin{aligned}
P &\approx P_t d/v && && (1)\\
&\approx (a + g\sin\theta + gC_r\cos\theta)(w+f)d && (\textit{load induced}) && (2)\\
&\quad + (0.5C_dA\rho)v^2 d && (\textit{speed induced}) && (3)
\end{aligned}
$$

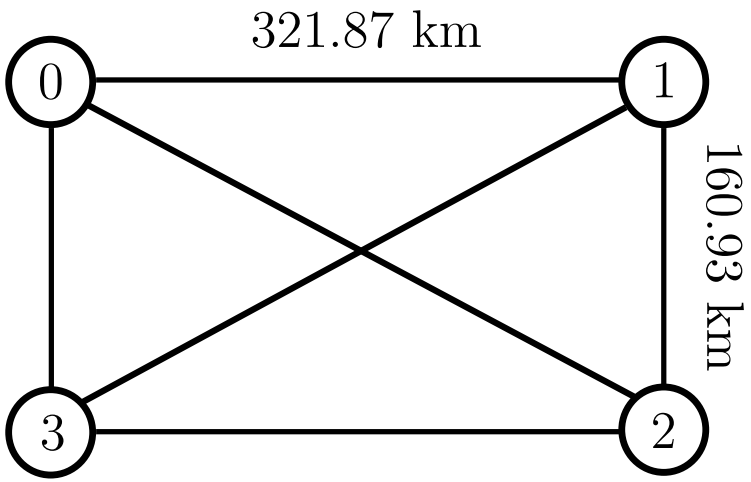
Typical fuel curve



Three main factors

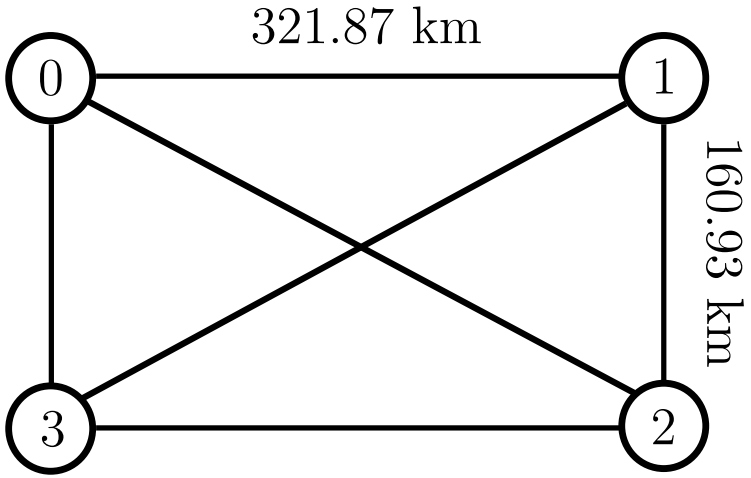
- Distance
- Load
- Speed

Distance



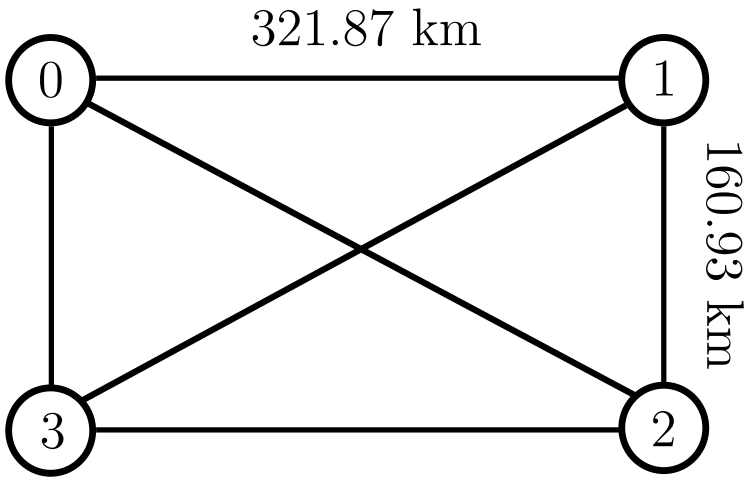
- curb (empty) weight equal to $w = 3$t and front surface 5.0m^2
- demand pattern as $q_1 = 1$, $q_2 = 1$ and $q_3 = 1$ (in t)
- no time windows and allow each vehicle to travel as slow as possible
- optimal tours?

Distance



- Two optimal tours of length 965.61 km
- Former tour consumes 192.56 kWh whereas the latter requires 183.79 kWh.
- Min. weighted load yields (0, 3, 2, 1, 0) as the optimal tour, with a saving of 4.55% in consumption with respect to the former.

Load



- demand pattern defined as $q_1 = 0.25$, $q_2 = 3.5$ and $q_3 = 0.25$ (in t)
- no time windows

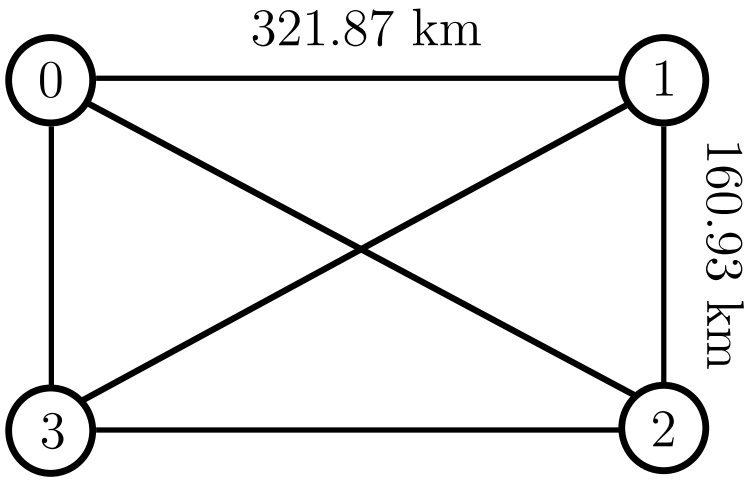
Load

Table: Comparison of distance and weighted load-minimising solutions

Distance-minimising solution						
Arc	Load	Distance	Speed	Load induced	Speed induced	Total
(0, 1)	3 + 4.00	200.00	40	61.40	23.25	84.65
(1, 2)	3 + 3.75	100.00	40	29.60	11.63	41.23
(2, 3)	3 + 0.25	200.00	40	28.51	23.25	51.76
(3, 0)	3 + 0.00	100.00	40	13.16	11.63	24.78
				132.66 kWh	69.76 kWh	202.42 kWh

Weighted load-minimising solution						
Arc	Load	Distance	Speed	Load induced	Speed induced	Total
(0, 2)	3 + 4.00	223.61	40	68.64	26.00	94.64
(2, 1)	3 + 0.50	100.00	40	15.35	11.63	26.98
(1, 3)	3 + 0.25	223.61	40	31.87	26.00	57.87
(3, 0)	3 + 0.00	100.00	40	13.16	11.63	24.78
				129.02 kWh	75.25 kWh	204.27 kWh

Speed



- $q_1 = 0.1$, $q_2 = 0.5$ and $q_3 = 0.1$ (all in t)
- visit customer 1 within 5.5 hours
- visit customer 2 within 25 hours
- visit customer 3 within 17 hours
- service time is 15 minutes for each customer

Speed

Table: Comparison of distance, load and energy-minimising solutions

Distance/Weighted load-minimising solutions						
Arc	Load	Distance	Speed	Load induced	Speed induced	Total
(0, 1)	3 + 0.70	200.00	60.98	32.45	54.06	86.52
(1, 3)	3 + 0.60	223.61	40.00	35.30	26.00	61.30
(3, 2)	3 + 0.50	200.00	40.00	30.70	23.25	53.95
(2, 0)	3 + 0.00	223.61	40.00	29.42	26.00	55.42
				127.87 kWh	129.32 kWh	257.19 kWh

Energy-minimising solution						
Arc	Load	Distance	Speed	Load induced	Speed induced	Total
(0, 1)	3 + 0.70	200.00	60.98	32.45	54.06	86.52
(1, 2)	3 + 0.60	100.00	46.00	15.79	15.39	31.17
(2, 3)	3 + 0.10	200.00	42.94	27.19	26.86	54.05
(3, 0)	3 + 0.00	100.00	40.00	13.16	11.63	24.78
				88.59 kWh	107.93 kWh	196.52 kWh

But this is not the whole story! There are costs in play:

- CO_2 costs (e per tonne):
  - Shadow price of carbon at £27/t of CO_2 emitted for year 2010, and to increase it by 2% for each subsequent year (DEFRA).
- Fuel costs (c_f per litre):
  - £1/L for the UK (The Automobile Association Limited, 2009).
  - 1L of gasoline provides 8.8 kWh of energy.
- Driver costs (p per hour):
  - Hourly wages in the range of £7.80 to £8.50 in the UK and of \$14.26 to \$18.60 in the United States (Payscale, 2009). We use £8.

Back to the original instance with no time windows.

Table: Comparison of costs

Cost (£)				
Problem	CO_2	Fuel	Driver	Total
Min. distance	7.20	115.01	199.14 (24.89h)	321.36
Min. weighted load	7.27	116.06	214.34 (26.79h)	337.68
Min. energy	7.13	113.77	199.14 (24.89h)	320.03
Min. cost	8.84	141.11	154.58 (19.32h)	304.53

Bektaş, T. and Laporte, G. (2011) The Pollution-Routing Problem. *Transportation Research Part B: Methodological* 45(8): 1232–1250.

Financial Times, 2 June 2015

"Carbon must have a higher price tag if the risk of catastrophic global warming is to be contained .. the most developed market for carbon emissions is in Europe, where they trade at 7 Euros per tonne .. According to Britain's Committee on Climate Change this will have to rise tenfold by 2030 and three times again by 2050".

- What if the per tonne price of CO_2 was £57 ($\approx$ \$95; Tol, 2005).
  1. Cost of CO_2 = £18.66
  2. Cost of fuel = £141.11
  3. Cost of driver = £154.58
  4. Total Cost = £314.35
- What if the per tonne price of CO_2 was £213 ($\approx$ \$350; Tol, 2005).
  1. Cost of CO_2 = £62.53
  2. Cost of fuel = £126.55
  3. Cost of driver = £173.95
  4. Total Cost = £363.04

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  1. Cost of CO_2 = £62.53
  2. Cost of fuel = £126.55
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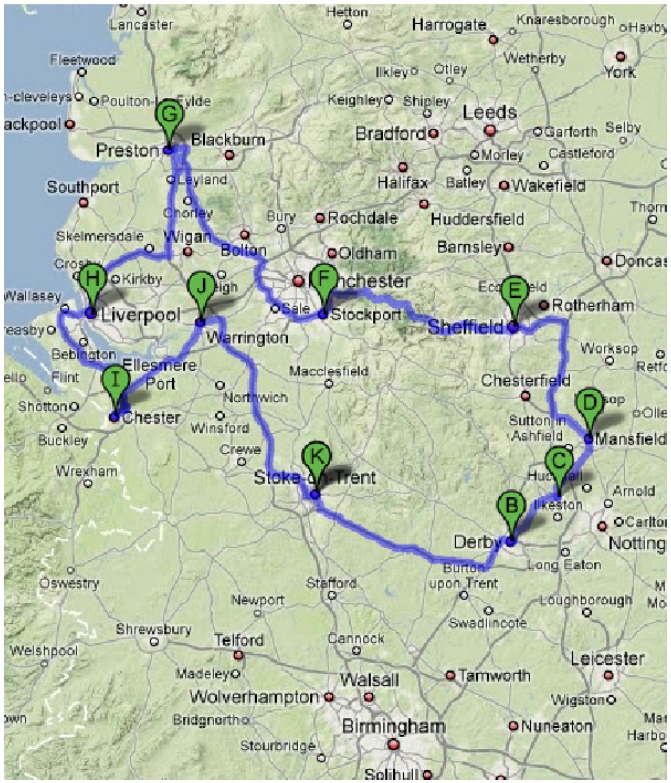
  4. Total Cost = £363.04

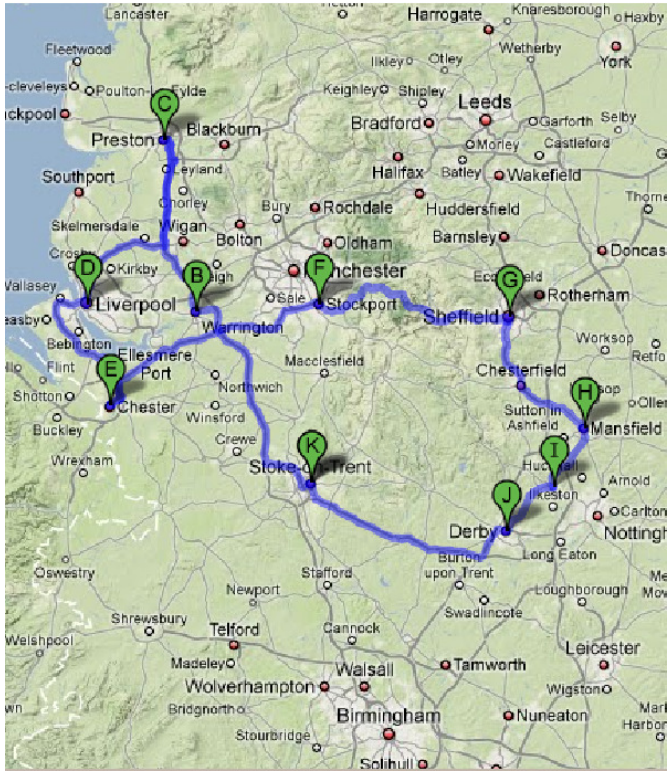
Sample solutions

Minimising distance



Stoke-on-Trent → Derby → Eastwood → Mansfield → Sheffield → Stockport → Preston → Liverpool → Chichester → Warrington
455.77 km, 89.71 kWh.

Minimising energy



Stoke-on-Trent → Warrington → Preston → Liverpool → Chester → Stockport → Sheffield → Mansfield → Eastwood → Derby
464.13 km, 87.56 kWh.

Decelaration

McKinnon, A.C. (2016) Freight Transport Deceleration: Its Possible Contribution to the Decarbonisation of Logistics. *Transport Reviews* 36(4): 418–436.

- Schneider lowered maximum speed for its fleet of 10,600 trucks from 63mph (101 km/h) to 60mph (96.5 km/h), reducing annual consumption by 17 million litres
- Con-way Freight brough down maximum speed from 65 to 62 mph, saving 12.1 million litres of fuel annually
- Limiting the speed of vans and light trucks in the Netherlands to 110 km/h cut fuel consumption by 5%

"Speed reduction is recognised to be one of the most cost-effective means of decarbonising the road freight sector."

Average speed enforcement goes live in Edinburgh

September 5, 2017

Scotland's first average speed camera system on a local road went live in Edinburgh on Monday. The system, which has undergone a period of testing since its installation in May, has been introduced on Old Dalkeith Road to improve safety, reduce the number of road casualties and encourage speed compliance.

During the years 2013-15 there were six injury collisions on this stretch of road, including three resulting in serious injury or fatality. Speed surveys have also identified a high proportion of vehicles travelling above the limit.

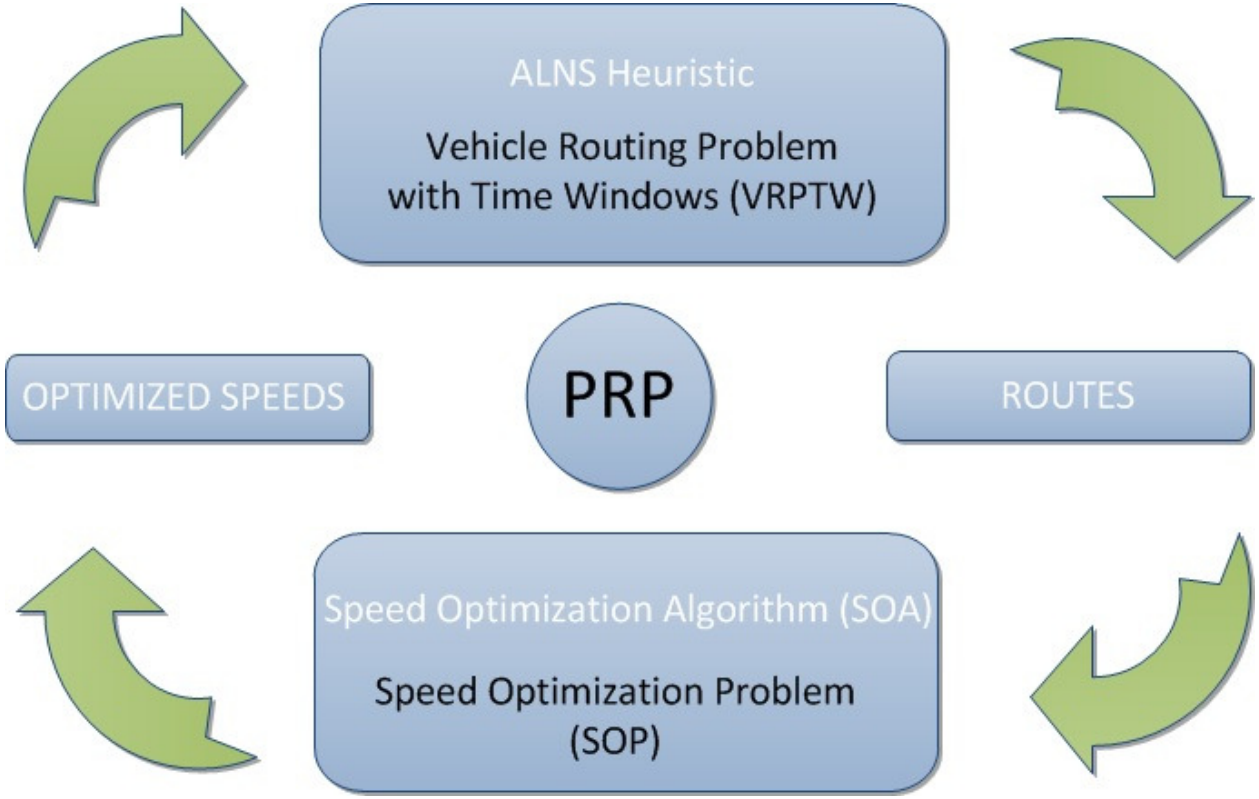
Part III

Algorithmic and Computational Challenges

Solution algorithm for the PRP

- PRP can be modelled as a nonlinear programming formulation.
- An integer linear(ised) program can only solve up to (some) 20 nodes optimally
- There are two different problems: routing and speed optimisation (SOP)
- We suggest two approaches:
  1. ALNS + SOP within SA
  2. ALNS + SOP (+others) within GA

An iterative approach



Adaptive large neighbourhood search (ALNS)

- Initial solution via the Clarke and Wright (1964) heuristic
- ALNS applies several mechanisms to obtain neighbours of a given solution:
  - Removal operators
  - Insertion operators
- Embedded within a simulated annealing framework

More on ALNS

- Ropke and Pisinger, 2006, An adaptive large neighbourhood search for the pickup and delivery problem with time windows, Trans Sci 40: 455–472.
- Shaw, 1998, Using constraint programming and local search methods to solve vehicle routing problems, LNCS Vol. 1520: 417–431.

The Speed Optimization Problem (SOP)

Given a feasible path $(0, 1, \ldots, i, i+1, \ldots, n)$ of nodes all served by a single vehicle, the SOP consists of finding the optimal speed on each link of the route between successive customers such that an objective function comprising fuel consumption costs and driver wages are minimised.

Speed optimisation in maritime logistics

- Hvattum, L.M., Norstad, I., Fagerholt, K. and Laporte, G. (2013) Analysis of an exact algorithm for the vessel speed optimization problem, *Networks*, 62(2): 132–135.
- Norstad, I., Fagerholt, K. and Laporte, G. Tramp ship routing and scheduling with speed optimization. *Transportation Research Part C: Emerging Technologies*, 19(5):853–865, 2010.

- SOP can be formulated as a NLP
- SOP can be solved in a polynomial time using a recursive algorithm
- Runs in two stages:
  1. Calculate optimal speeds to minimise the total cost function
  2. Recalculate speeds to minimise fuel consumption
- Improvements on given routes yield average cost reductions between 2–3%
- A large majority of solutions use an optimal speed minimising fuel *and* driver costs

Challenges

Some algorithmic challenges have been tackled:

- Load dependent (energy minimising) PRP (Fukasawa et al. 2015)
- Other advanced (mat)heuristics for the PRP (Kramer et al., 2015)
- A branch-and-price algorithm for the PRP assuming fixed speeds (Dabia et al., 2014)
- A disjunctive convex programming approach to the PRP (Fukasawa et al., 2016)

but others still remain for the PRP:

- Better formulations (load?)
- An exact algorithm or lower bounding schemes
- Decompositions

Part IV

Variations

- Multiobjective problems
- Heterogeneous fleet
- Time dependency

The bi-objective PRP

One vs multiple objectives:

- Looks at two objectives separately; (i) minimising fuel and (ii) minimising driver time
- Four multi-criteria methods

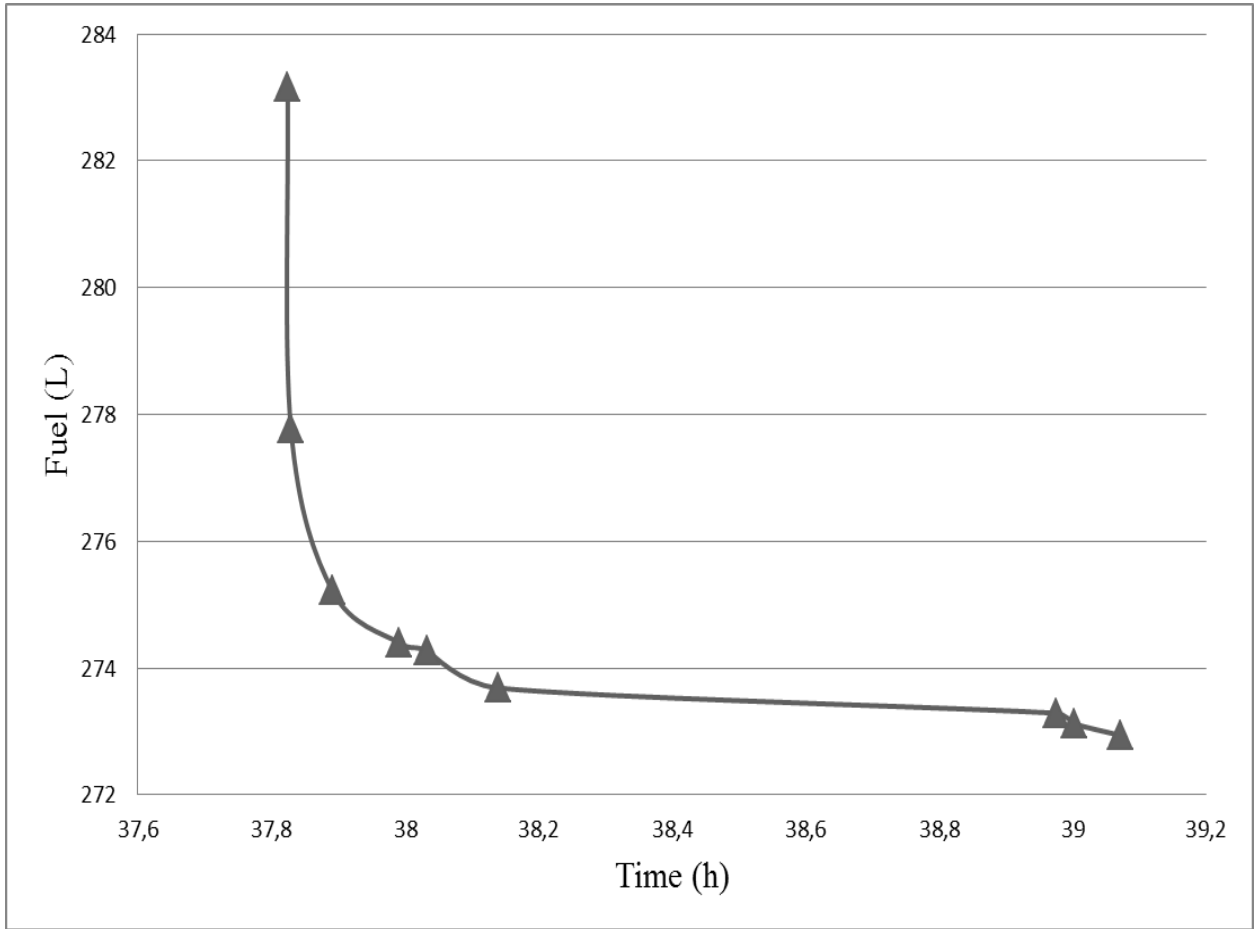


Figure: Sample instance with limits 20–100 km/h

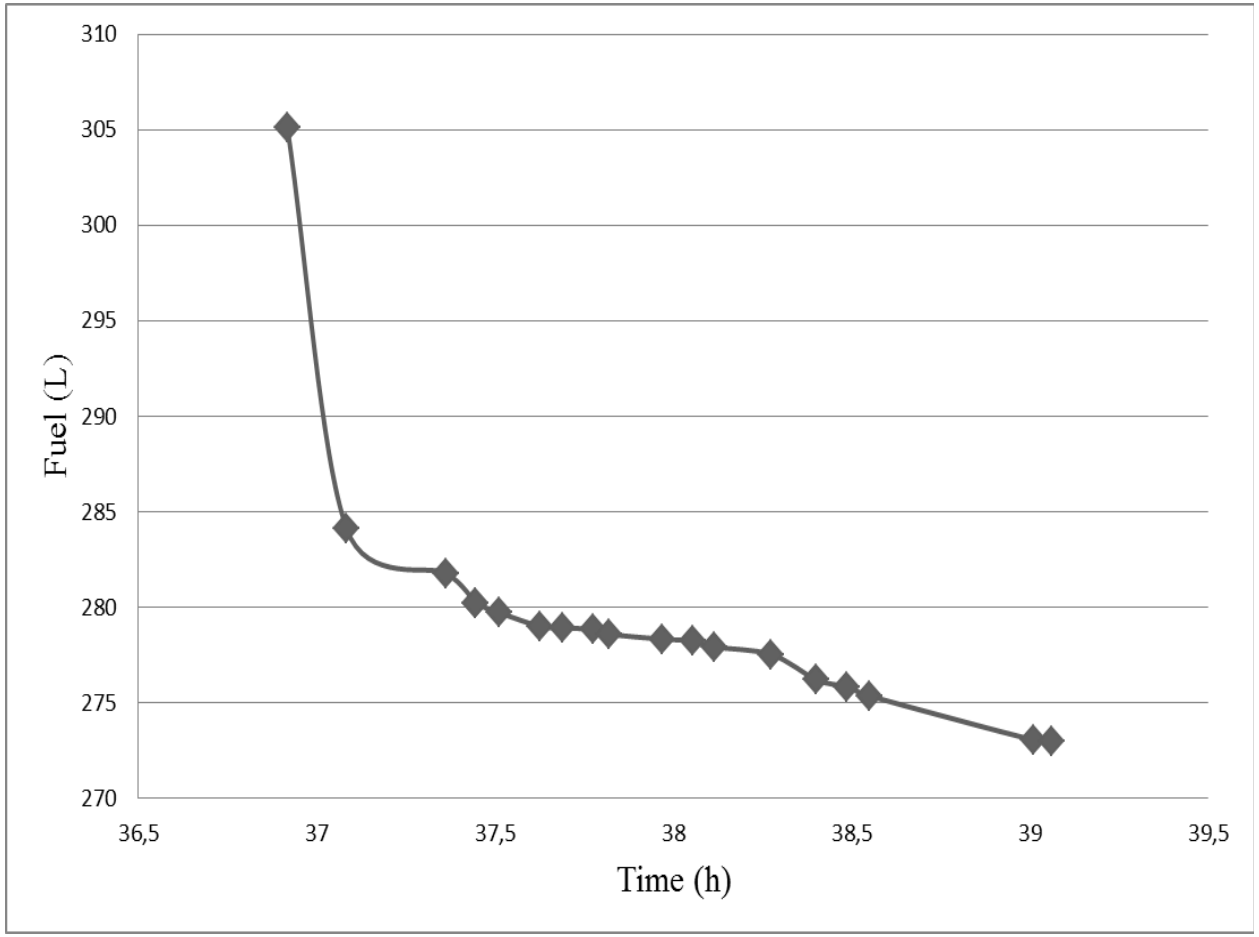
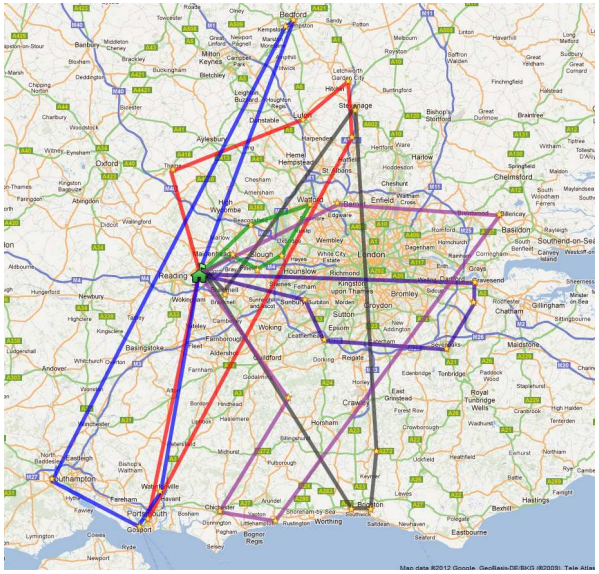
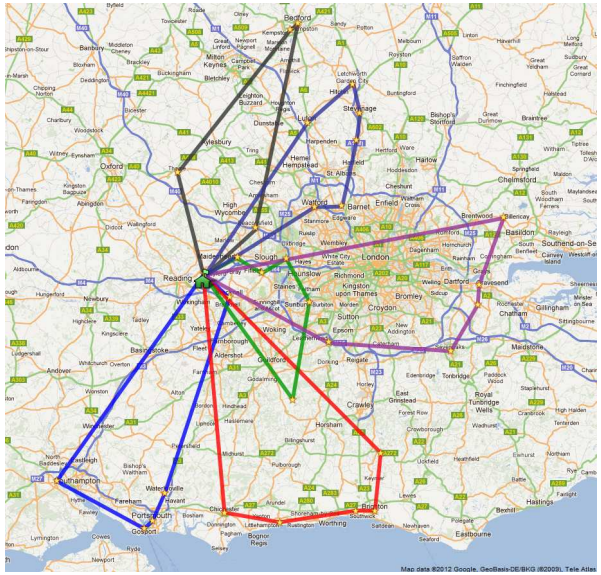


Figure: Sample instance with limits 20–100 km/h

Two non-dominated solutions for a 30-node instance



(a) Time-minimising



(b) Fuel-minimising

- A: 1621.7 kilometers, 321.57 liters diesel fuel, 21.16 hours, 1008.12 kg CO_2
- B: 1270.1 kilometers, 233.54 liters diesel fuel, 23.21 hours, 732.15 kg CO_2
- The 9.7% increase in driving time leads to a 27% saving in energy requirements.
- 8.8% reduction in driving time from but a 37.7% increase in CO_2

Heterogeneous PRP

Uniform vs varied fleet:

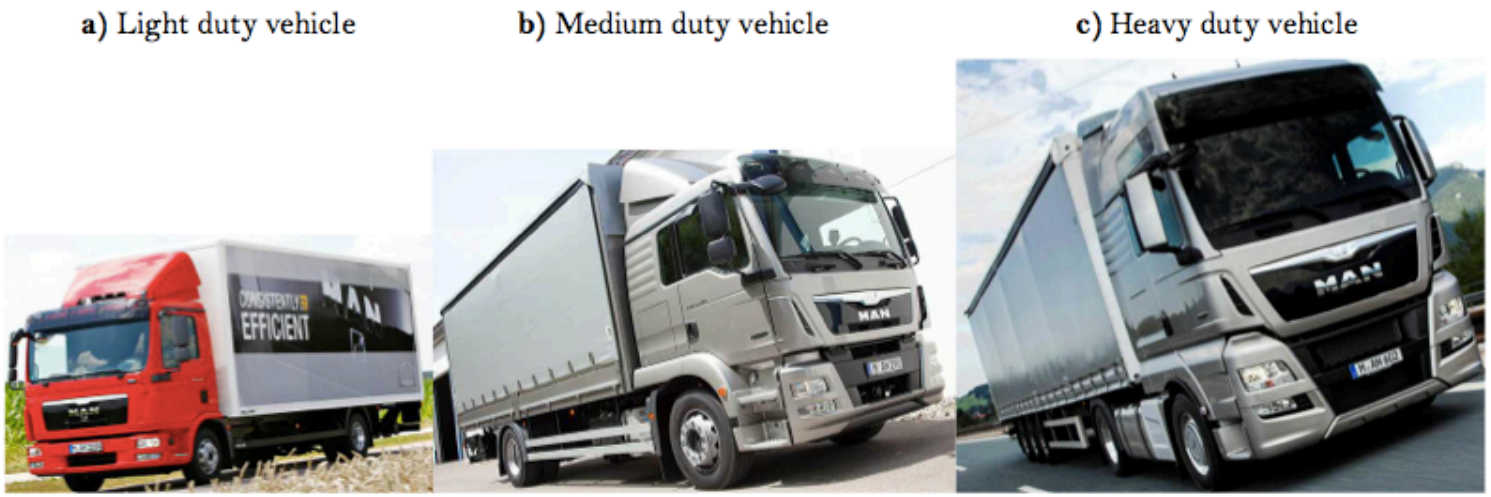


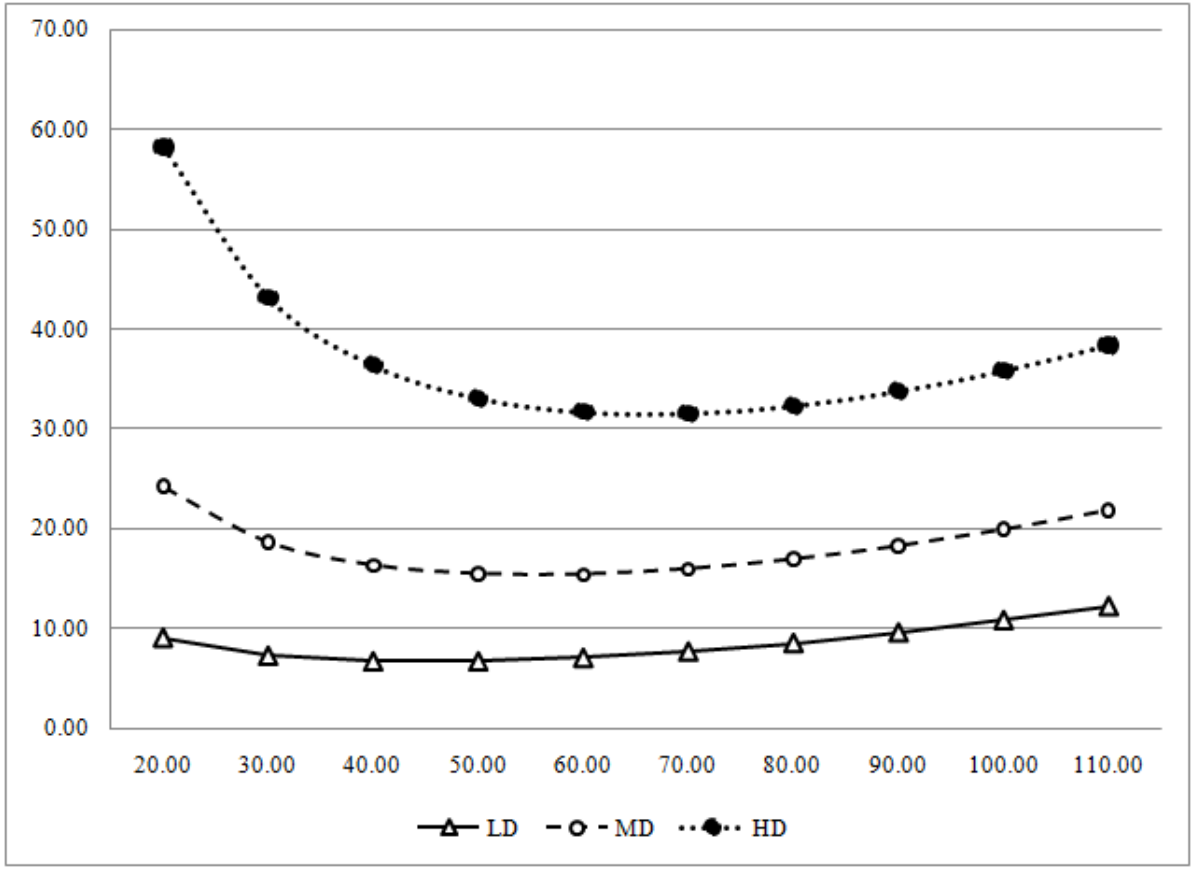
Figure 1: Three vehicle types (MAN, 2014)

Parameters

Table: Vehicle specific parameters

Description	Light duty	Medium duty	Heavy duty
curb weight (kg)	3500	5500	14000
maximum payload (kg)	4000	12500	26000
vehicle fixed cost (£/day)	42	60	95
engine friction factor (kj/rev/liter)	0.25	0.20	0.15
engine speed (rev/s)	38.34	36.67	30.0
engine displacement (liter)	4.5	6.9	10.5
coefficient of aerodynamics drag	0.6	0.7	0.9
frontal surface area (m^2)	7.0	8.0	10.0

Sensitivity to parameters



Heterogeneous PRP

- On average, total cost is:
  - 48.30% vehicle cost
  - 31.85% driver cost
  - 19.85% fuel and emissions
- MD vehicles preferred in a homogeneous fleet.
- Heterogeneous fleet with fixed speed of 100 km/h is better than using a homogeneous fleet of vehicles with optimised speeds.
- Average utilisation is 96% for LD, 94% for MD and 37% for HD, but 69% for heterogeneous fleet.

Time-dependency in the PRP

Time (in)dependency: Time-dependent PRP

- So far, a "single" time-zone has been assumed where speeds can be changed within limits.
- What about congestion and its effects?

Congestion and the VRP

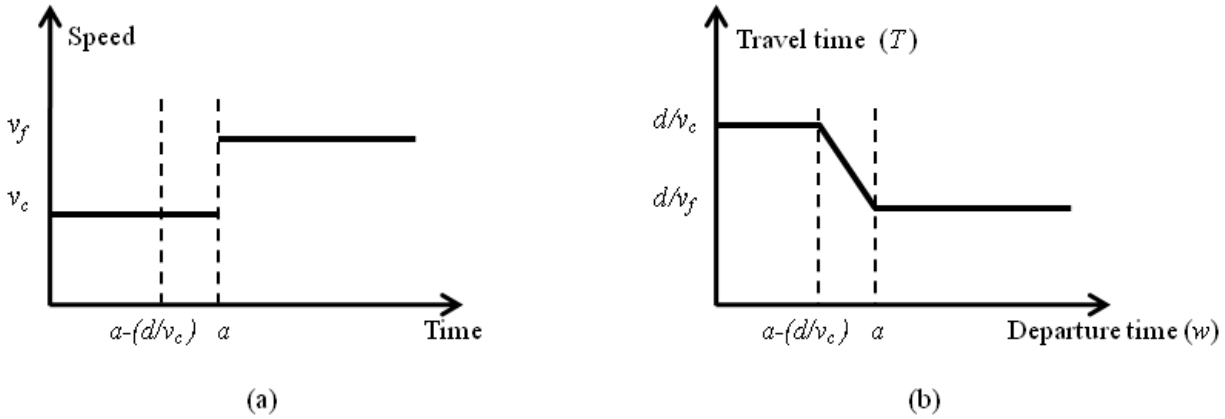
- Maden, W., Eglese, R.W., Black, D. (2010) Vehicle routing and scheduling with time-varying data: a case study, *Journal of the Operational Research Society* 61(3): 515–522.
- Figliozzi, M.A. (2010) Vehicle routing problem for emissions minimization, *Transportation Research Record* 2197:1–7.

Time-dependency in the PRP

Two-level speed profile:

1. v_f: free-flow speed
2. v_c: congestion speed

An initial period of congestion lasting a units of time



Three regions: *all congestion*, *transient* and *all free-flow*.

Two-level speed profile

In the TDPRP, the aim is to:

- Solve a PRP with the two-level speed profile
- And consider a post-service (idle) waiting time at customers

Two policies on driver wage:

1. driver paid from beginning of the time horizon until they return to depot,
2. driver paid only for time spent away from depot (no pay for wait at depot).

Analytical results - insights

In the case of no time windows:

- If the driver is paid from time zero, either leave immediately or wait until the end of the congestion period.
- If the driver is paid from the start time of travel, it is always optimal to wait until the end of the congestion period.
- In both cases, there is an optimal free-flow speed.

In the case of time windows:

- (Earliest) optimal departure time from the depot is non-decreasing with respect to the time windows l and u.
- Optimal free-flow speed (when used) is non-increasing in l and u.

For more on the ALNS and the bi-objective PRP

- Demir, E., Bektaş, T. and Laporte, G. (2012) An adaptive large neighborhood search heuristic for the Pollution-Routing Problem, *European Journal of Operational Research* 223(2): 346–359.
- Demir, E., Bektaş, T. and Laporte, G. (2012) The bi-objective Pollution-Routing Problem, *European Journal of Operational Research* 232(3): 464–478.

For more on the HFPRP

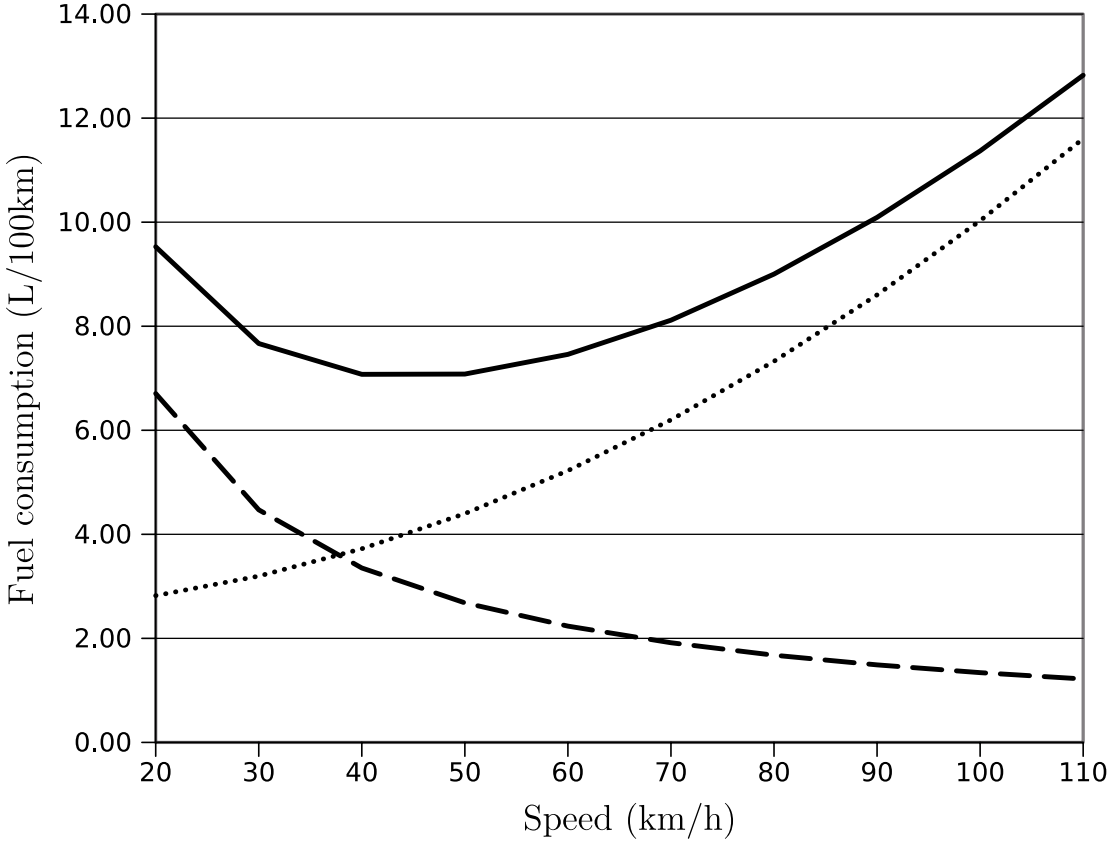
- Koç, Ç., Bektaş, T., Jabali, O. and Laporte, G. (2014) A hybrid evolutionary algorithm for heterogeneous fleet vehicle routing problems. Forthcoming in *Computers & Operations Research*.
- Koç, Ç., Bektaş, T., Jabali, O. and Laporte, G. (2014) The fleet size and mix pollution-routing problem. *Transportation Research Part B: Methodological* 70: 239–254.

For more on TDPRP

- Franceschetti, A., Honhon, D., Van Woensel, T., Bektaş, T. and Laporte, G. (2013) The time-dependent pollution-routing problem. *Transportation Research Part B: Methodological*, 56: 265–293.

Part V

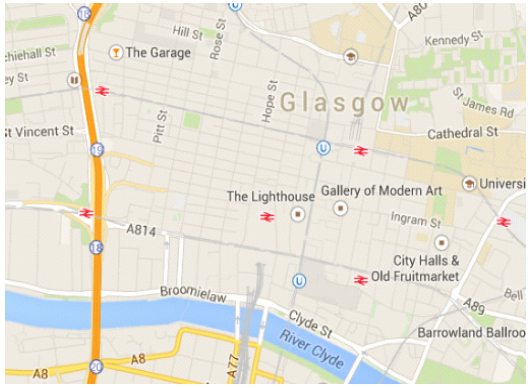
City Logistics


14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Fuel consumption (L/100km)
20
30
40
50
60
70
80
90
100
110
Speed (km/h)

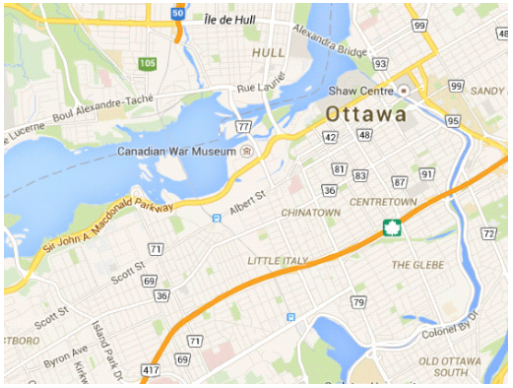
Speed zones in cities for the environment and public safety:

- 15 mph (25 km/h): alleys, narrow residential roadways
- 20 mph (32 km/h): business districts, school zones
- 25 mph (40 km/h): residential districts, public parks, ocean shores

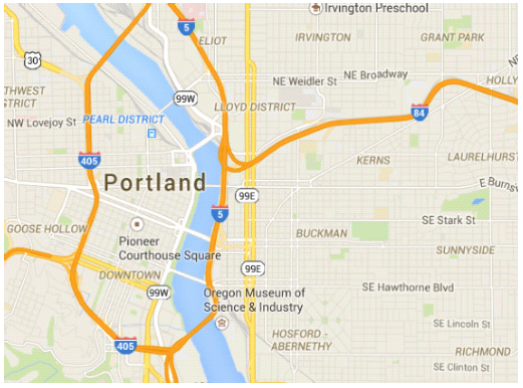
(a) Glasgow

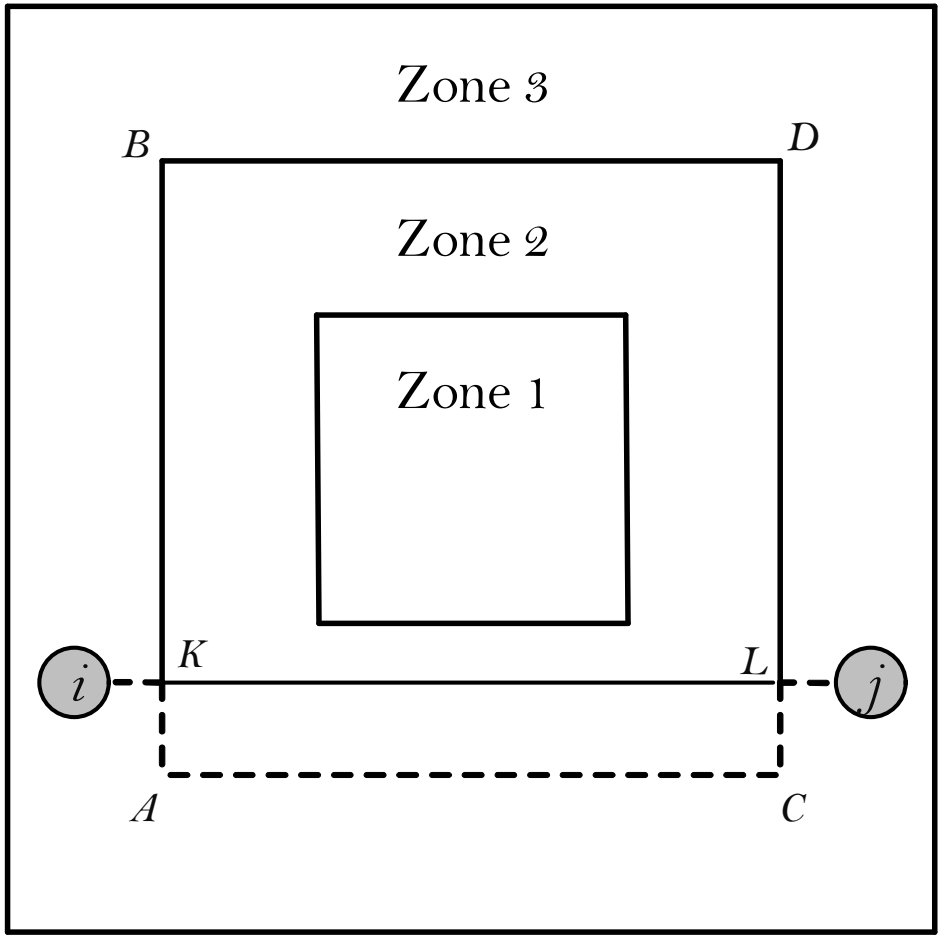


(b) Ottawa

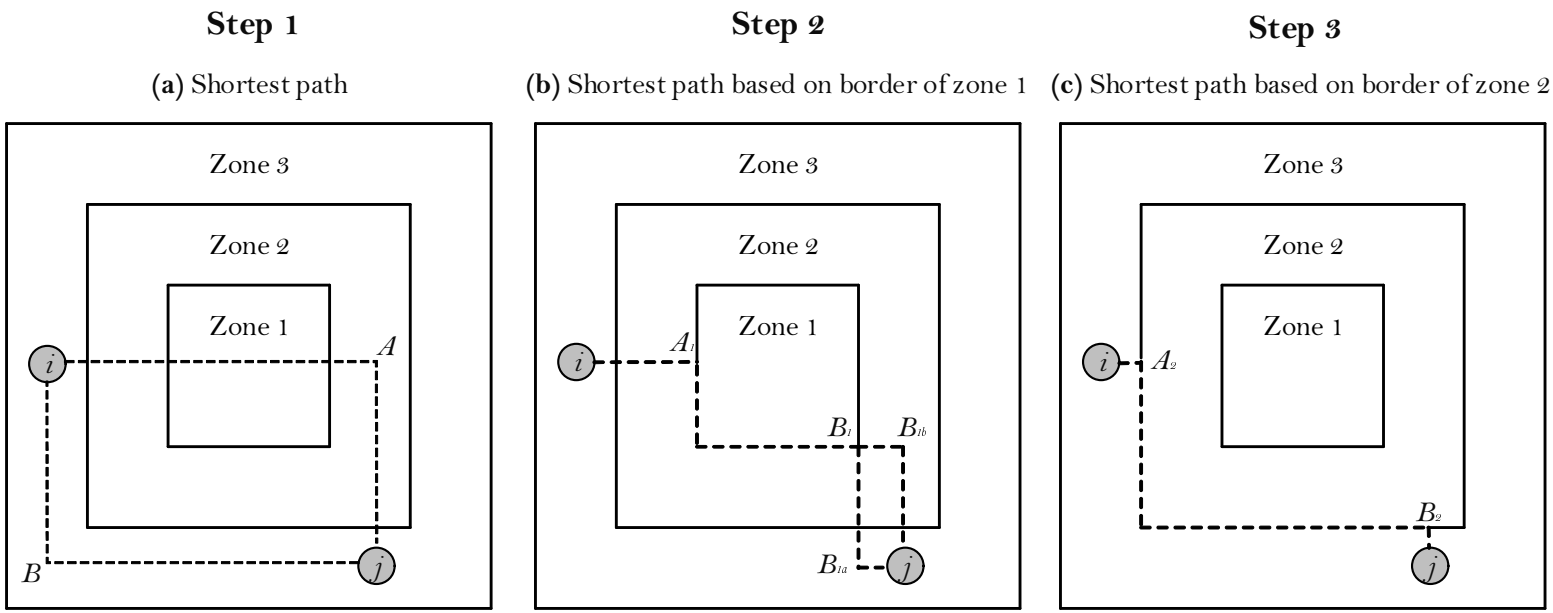


(c) Portland




Zone 3
B
D
Zone 2
Zone 1
K
L
i
j
A
C

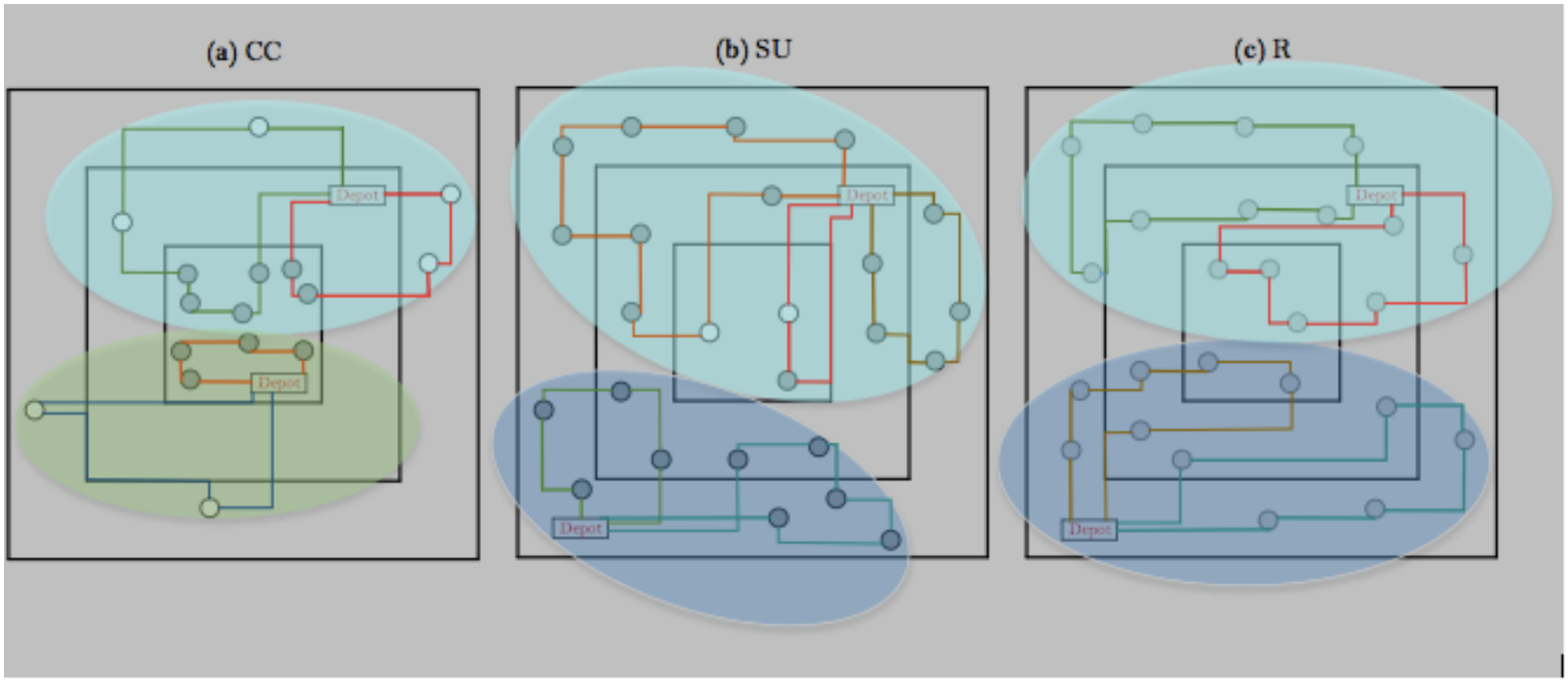
To find a cheapest path between a pair of nodes, we use a procedure that is based on *contorting* the shortest distance.



Impact of:

- Location
- Fleet Composition
- Routing

We use a version of ALNS to solve the joint problem.


(a) CC
(b) SU
(c) R
Depot
Depot
Depot
Depot
Depot
Depot

Results conducted on randomly generated instances with 25–100 customers and 4–10 depots suggest that:

- A shortest path in an urban setting is not always a fastest, cheapest or least polluting
- Highest costs are attained when all customers are located only in the city centre
- It is preferable to locate the depots outside the city centre (average cost savings of 35%)
- Use of heterogeneous vs homogeneous fleet decreases costs by up to 17%

For more

- Koç, Ç., Bektaş, T., Jabali, O. and Laporte, G., 2014. The impact of depot location, fleet composition and routing on emissions in city logistics. *Transportation Research Part B: Methodological*, 84: 81–102.

Part VI

Looking Ahead

(Featuring sentiments from anonymous reviewers...)

Referee comments

"Why would a manager then select a solution different from the cost minimizing one ... But would they really care about a small reduction in CO_2 emissions?

Referee comments

"It is not at all clear to me how much freedom a driver has to pick the 'optimal' speed... fail to argue to which degree speed can be varied without causing any major negative externalities ... I just try to imagine a lorry going 65 km/h on a motorway, saving CO_2 emissions, but infuriating drivers, causing congestion and accidents. This may have far larger negative effects than the positive effects on society from GHG emission savings ..."

Referee comments

"... but I don't think this research direction currently looks fruitful"

Referee comments

"Given these trade-offs, I don't think anyone in industry would use the recommended routing plans."

Referee comments

"Yet another VRP with a different objective function?"

Remarks

- VRP studies have mainly been "governed" by the existing infrastructure and societal rules
- Inform policy making:
  - Dedicated freight lanes with fixed speed
  - Driver behaviour and training
  - Driver wages, carbon costs or taxes
- Inform technological developments or innovations
  - Engine efficiency - is it worth it?
  - Fleet design, aerodynamics
- Collaboration with other disciplines

Next steps?

- Still embryonic
- Only begun to scratch the surface

Algorithmic:

- (More) algorithms solve the PRPs
- Uncertainty in travel times: expected vs unexpected
- Dynamic assignments or real-time reassignments
- Time invariant vs dependent

Environmental:

- Other externalities: noise, accidents

Thank you for your attention.

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