Sustainable Supply Chains

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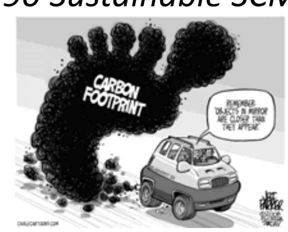
Sustainable Logistics Initiative

Analyzing the practical implications of considering transportation CO2 emissions in logistics decisions

- Vehicle assignment
- Vehicle routing
- Network flows
- Replenishment strategies

Graduate level course at MIT
SCM.290 Sustainable SCM

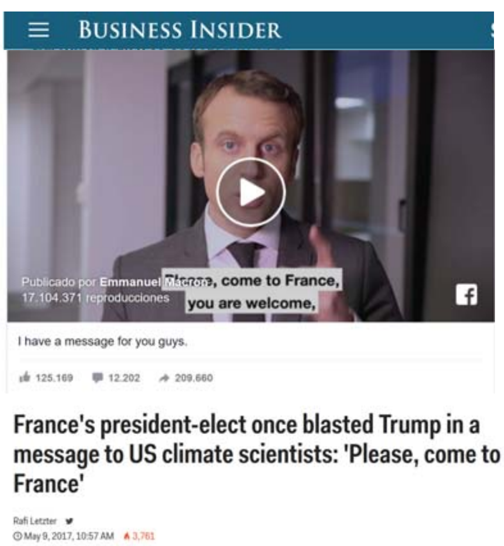


Debate regarding Sustainability

The Guardian – Nov 13, 2016: Trump seeking quickest way to quit Paris climate agreement, says report. https://www.theguardian.com/us-news/2016/nov/13/trump-looking-at-quickest-way-to-quit-paris-climate-agreement-says-report

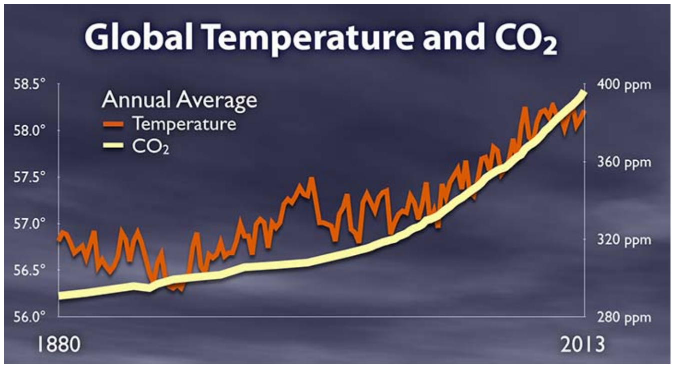
"…the head of EPA says he doesn't think carbon dioxide causes global warming" –The Boston Globe (2017)

Debate regarding Sustainability



"I do know how your new president now has decided to jeopardize your budget, your initiatives, and he is extremely skeptical about climate change," he said… I have no doubt about climate change… Come to France, you are welcome" –Business Insider (2017)

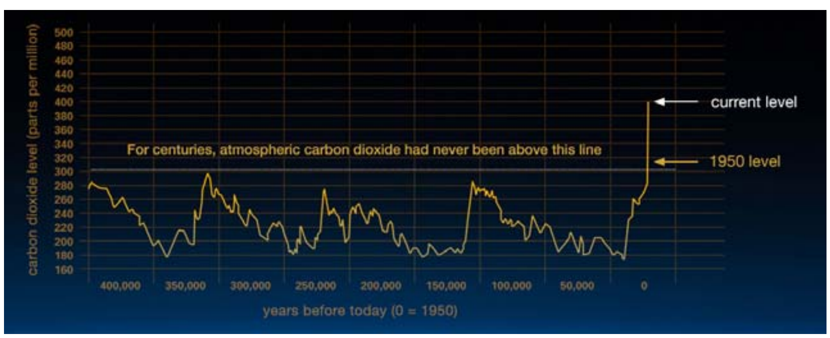
However Science confirms the opposite



"… research, …and the fact that no models can replicate this century's warming without pumping up carbon dioxide… give scientists confidence that human carbon emissions are driving the globe's temperature higher"

Source: National Climate Assessment (2014). http://www.climatecentral.org/gallery/graphics/co2-and-rising-global-temperatures

However Science confirms the opposite



"We have achieved the highest level of carbon dioxide in the atmosphere in the history of humanity"

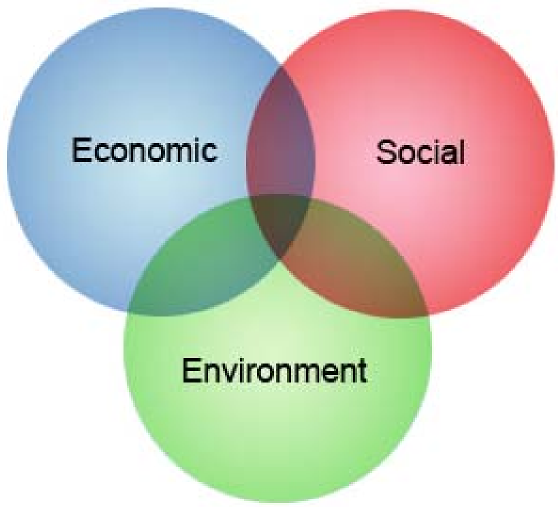
– NASA Global Climate Change (2017)

Sustainability

Why companies should care?

When short-term perspective is misleading…

Sustainability is about the "future"… it is a long-term concept on survival



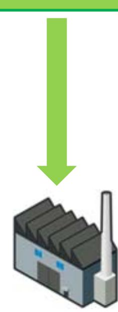
Pressures on companies to act

Feike Sijbesma, CEO

DSM
BRIGHT SCIENCE. BRIGHTER LIVING.

**Dutch multinational active in the fields of health, nutrition and materials. It employs 20,750 people in 50 countries and posted net sales of €7,722m.*

Long-term survival
Resource scarcity



"We cannot succeed in a world that fails"

Source: Fransoo J. C. (2011)

Pressures on companies to act

Source: Fransoo J. C. (2011)

Some examples from Nielsen (2015)

Green Generation: Millennials say Sustainability is a shopping priority

- 66% of global respondents say they're willing to pay more for products and services that come from companies that are committed to positive social and environmental impact, up from 55% in 2014, and 50% in 2013.
- A company being environmentally friendly (+13 pp) ranked the highest in the comparison.

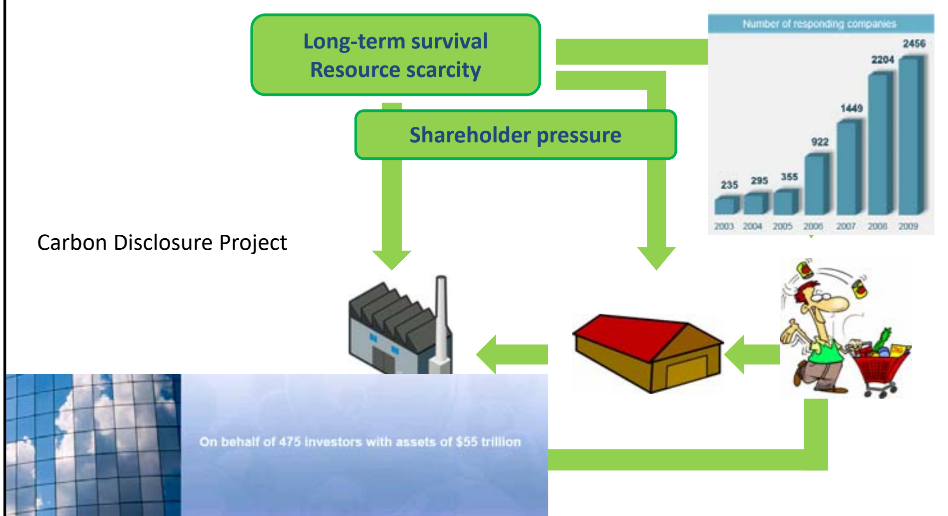
$600 billion

Amount spent by Millennial shoppers each year in the United States.

Source: Accenture https://www.accenture.com/us-en/insight-outlook-who-are-millennial-shoppers-what-do-they-really-want-retail Accessed March 2017

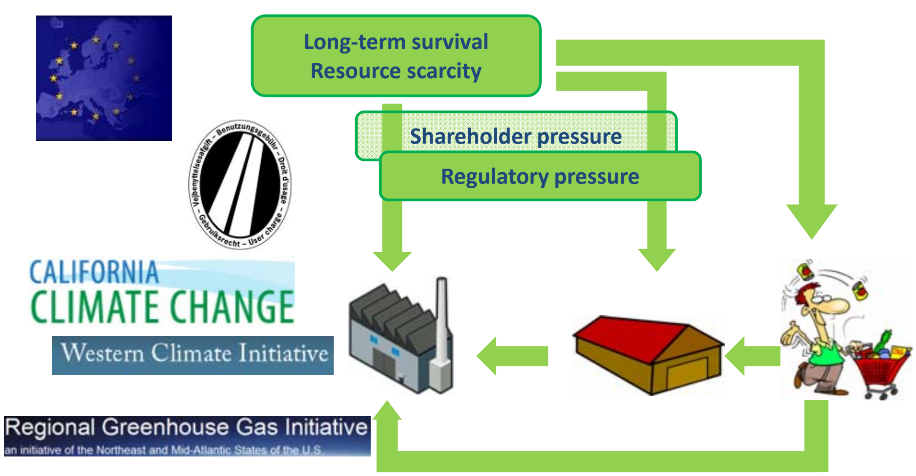
Source: http://www.nielsen.com/us/en/insights/news/2015/green-generation-millennials-say-sustainability-is-a-shopping-priority.html Accessed March 2017

Pressures on companies to act



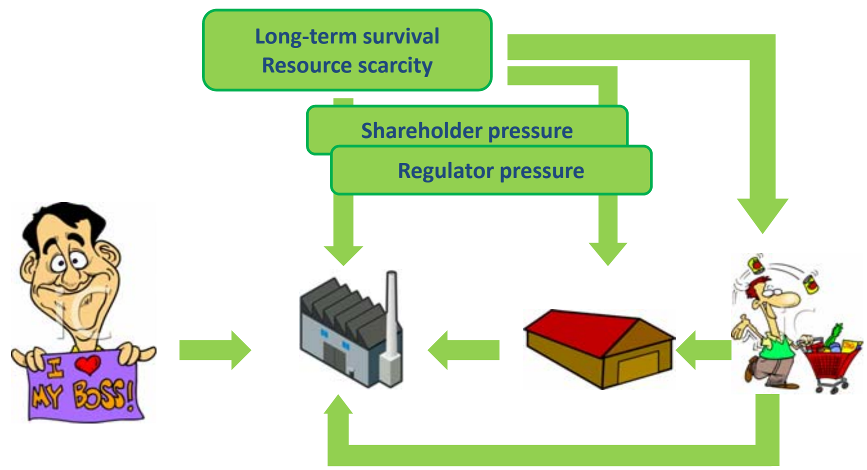
Source: Fransoo J. C. (2011)

Pressures on companies to act



Source: Fransoo J. C. (2011)

Pressures on companies to act



Source: Fransoo J. C. (2011)

Or purely cost-driven

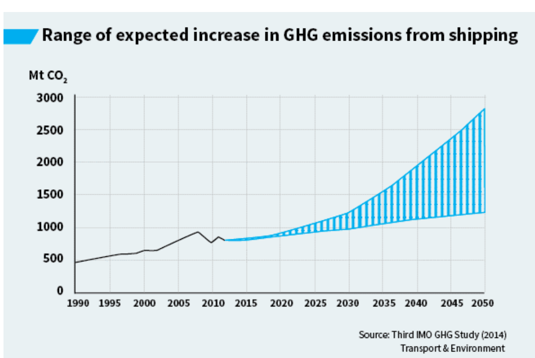
The **Top 10 Most Successful American Companies** from Fortune 500 **report their yearly CO2 emissions** in the Carbon Disclosure Project – Report on Climate Change (2016)

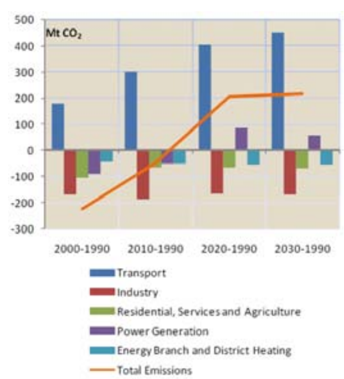
Consumer Electronics Association found that **companies measuring their carbon footprint** were able to reduce their power consumption by **5-25% per million dollars of revenue** (Vasan et al. 2014)

Edward Humes (2011), *Force of Nature: The Unlikely Story of Wal-Mart's Green Revolution*.

Impact of Transport Emissions

Transport emissions are by far the main contributor to emissions growth…

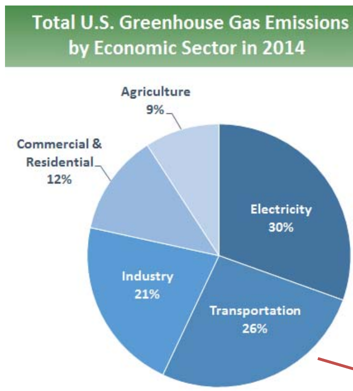




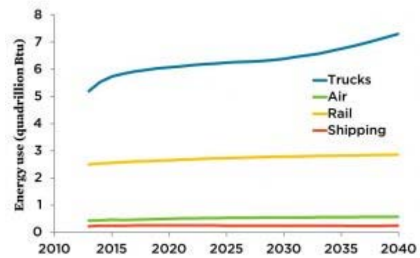
Source: European Commission (2007)

Source: Road to Paris: A climate deal must include aviation and shipping (2010). https://www.transportenvironment.org/road-paris-climate-deal-must-include-aviation-and-shipping

…. with freight transport contributing about 26% to the total emissions



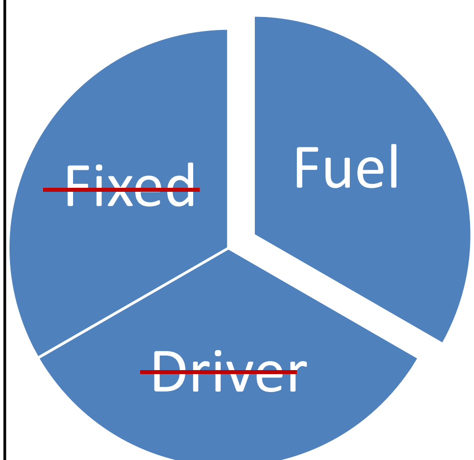
U.S. Environmental Protection Agency (2014). *U.S. Greenhouse Gas Inventory Report: 1990-2014.*



Over **90%** of the fuel used for transportation is **petroleum based**, which includes gasoline and diesel

Source: EPA (2014). https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

What about Transport Cost?



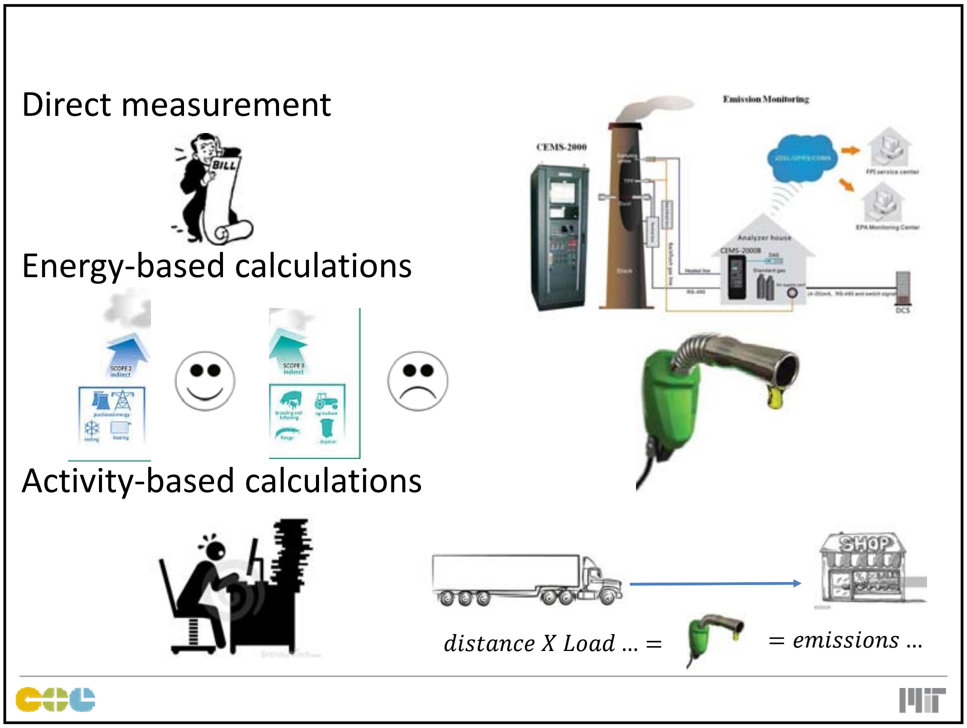
Fuel Consumption is the main transport cost during the *delivery operation*

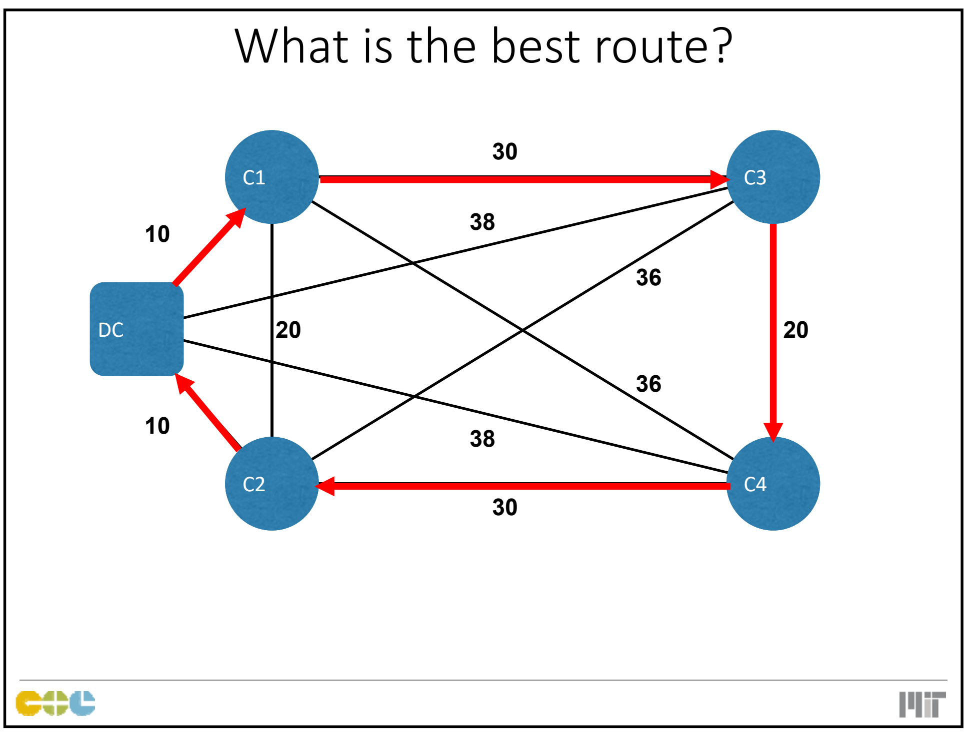
Sources: ATRI (2011) *Analysis of Operational Costs of Trucking.*

Different ways to tackle the challenge

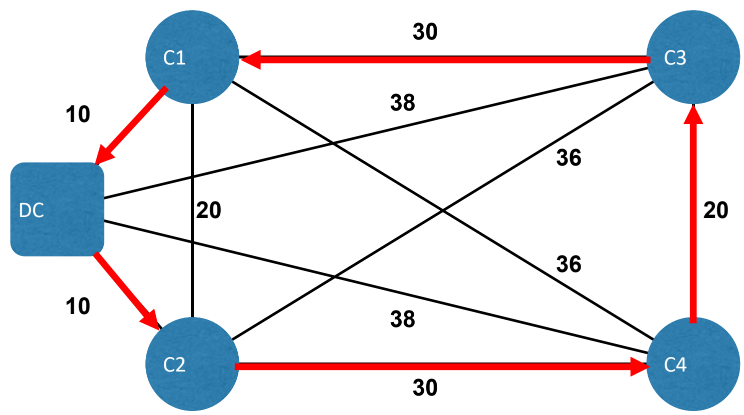
Massachusetts Institute of Technology

How to tackle transportation CO2 emissions


Direct measurement
BILL
Energy-based calculations
Activity-based calculations
Emission Monitoring
CEMS-2000
SHOP
distance X Load … =
= emissions …


What is the best route?
C1
C3
DC
C2
C4
30
38
10
36
20
20
36
10
38
30

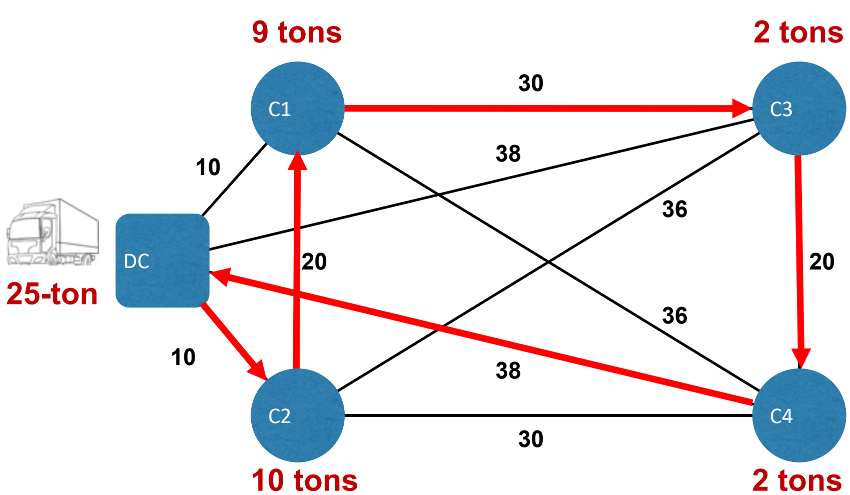
Is Distance-min enough?



Optimal distance/mileage (100*)

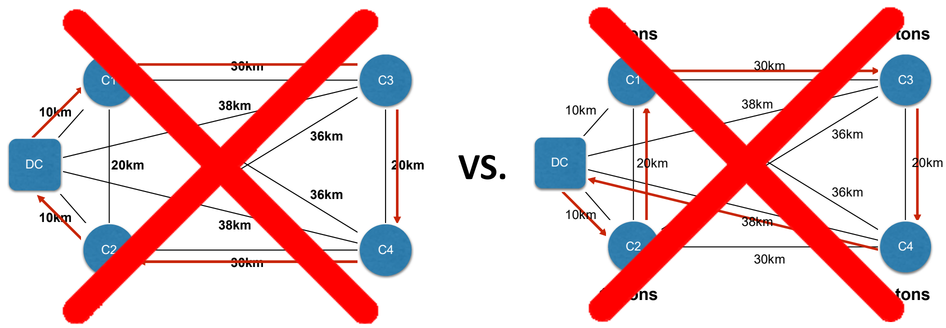
Can we assume that fuel consumption would be minimize as well?

Let's include now load information…



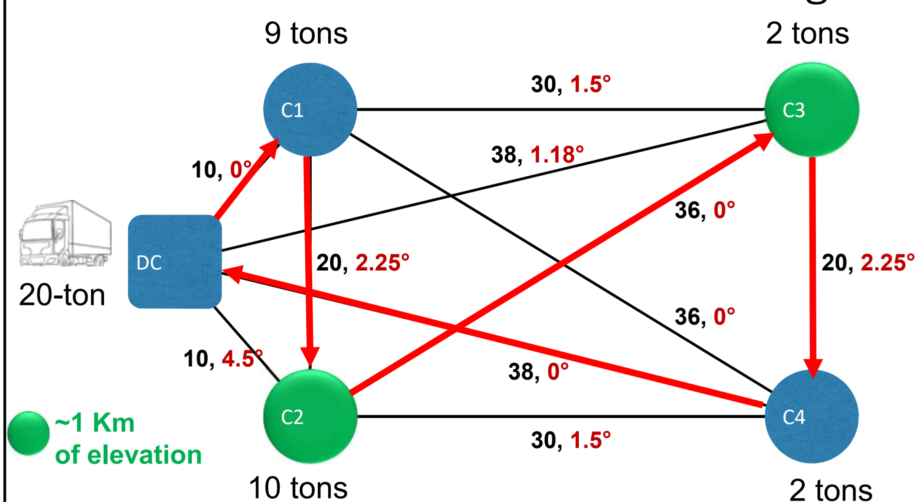
distance/mileage increases 18%...

Which solution is better in terms of fuel consumption?



We don't know the answer to that question.
What we do know is that probably both are wrong…

Let's include this time the road angles



distance/mileage increases 24%..
But with optimal fuel consumption (22% less)… ☺

A fun fact…

Including more complexity in the VRP by adding the load effect, but still assuming flat road, may actually be worse in terms of fuel than the distance-min solution…

Solution	Distance (km)	Fuel (L)
Distance Optimal 1	**100**	64.48 (+16.0%)
Distance Optimal 2	**100**	65.37 (+17.5%)
Fuel Optimal (Flat)	118 (+18%)	64.57 (+16.2%)
Fuel Optimal	124 (+24%)	**55.59**

How important is the road angle?

The second most common factor usually considered in transportation CO2 models is speed (it comes second after distance)

- Turkensteen (2017) considers the CMEM and shows that speed fluctuations (~acceleration) can increase computed fuel consumption by up to 80%.

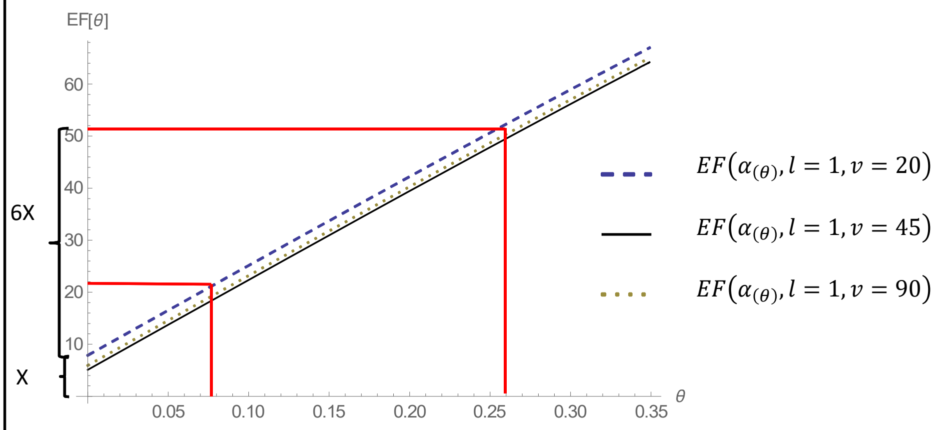
To exemplify the effect of the road angle wrt to speed, we assume the typical values for the parameters presented in Demir et al. (2012), and thus, the energy factor EF on each trajectory can be calculated as:

$$EF\left(\alpha_{(\theta)}, l, v\right) = \frac{33}{v} + 0.0046v^2 + (17.64 + 0.0028l)\ \alpha_{(\theta)}$$

How important is the road angle?

The effect of the angle increases as the load is heavier.

Let's take a conservative approach with load=1 Kg



$\theta = 4.5^o$

Velázquez-Martínez et al. (2016). "A new statistical method of assigning vehicles to delivery areas for CO2 emissions reduction". Transportation Research Part D

Preliminary conclusions

The energy consumption explained by the angle is way larger than the speed's contribution even when considering a maximum speed of v = 90 Km/hr

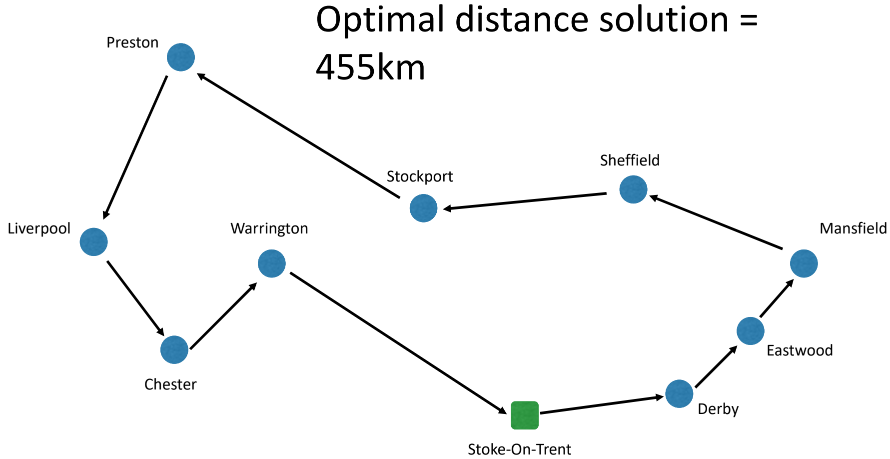
This conclusion leads to other research questions:

- What is the effect of topography in transportation Fuel consumption/CO2 emissions?
- What is the effect of topography in routing decisions?
- What is the effect of assuming planar road in routing decisions?
- How logistics decisions models should account for this effect?

Let’s take a look at some real examples

UK Example -(Bektas and Laporte, 2011)

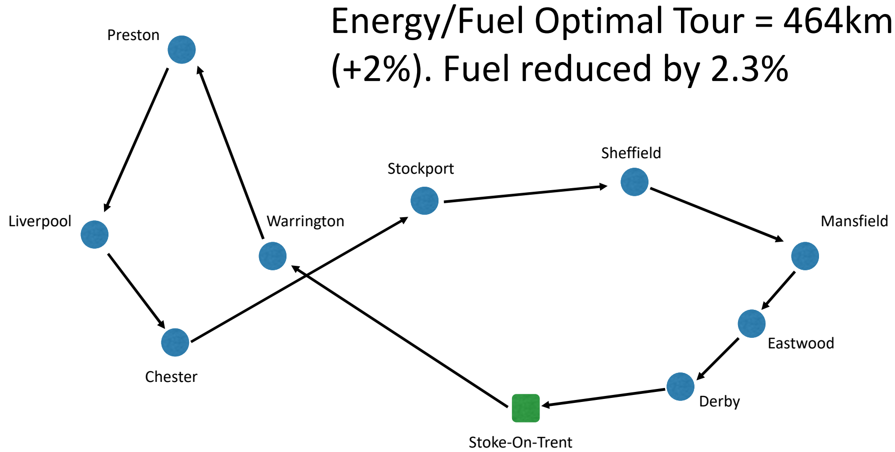
Optimal distance solution = 455km



Davydov D & Velázquez-Martínez J.C. (2017).

UK Example -(Bektas and Laporte, 2011)

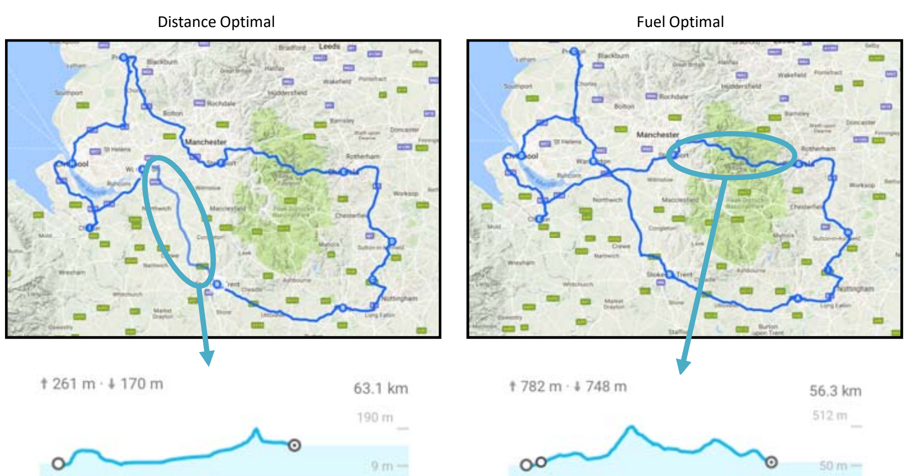
Energy/Fuel Optimal Tour = 464km (+2%). Fuel reduced by 2.3%



*as reported in Pollution-Routing Problem by Bektas et al. (2011)

Davydov D & Velázquez-Martínez J.C. (2017).

But the real world is a bit different..



$F_{\theta=0}$ = 17.76L
F = 19.13L
7.7% underestimation

$F_{\theta=0}$ = 18.52 L
F = 23.80 L
28.5% underestimation

Davydov D & Velázquez-Martínez J.C. (2017).

When solving the same problem we obtain all three solutions different

Fuel Optimal θ=0*

Distance Optimal* and Fuel Optimal θ≠0

Solution	Distance (Km)	Fuel (Liters)
Optimal Distance -(Bektas & Laporte, 2011)	455 (+5.5%)	67.2 (+5.3)
Optimal Fuel ($\theta = 0$) -(Bektas & Laporte, 2011)	464* (+10%)	70.6 (+10.4%)
Optimal Fuel ($\theta \neq 0$)**	**431**	**63.9**

Fuel optimal tours with $\theta = 0$ might actually being worse in distance and fuel

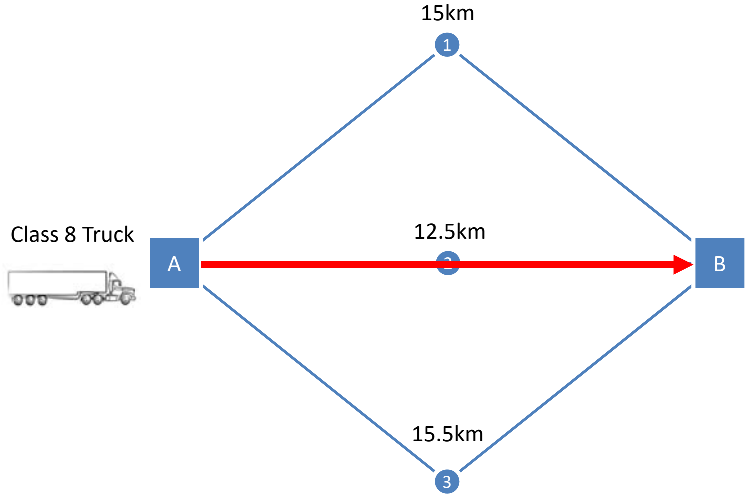
* Our data indicates 474km
** Our fuel optimal tour is also equal to our distance optimal solution.

Using the model to estimate a trajectory from A to B

Truck Class 8 specifications

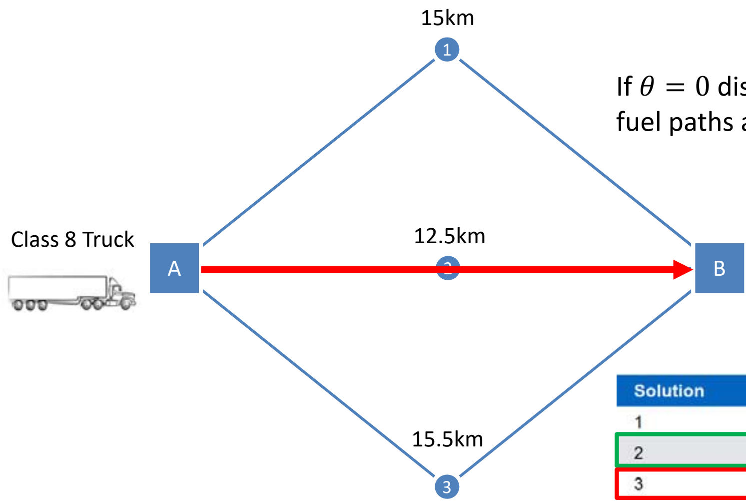
w	Curb-Weight (kg)	**14,000**
l	Max load (kg)	**26,000**
ξ	Fuel-to-air mass ratio	**1**
k	Engine friction factor (kJ/rev/L)	**0.15**
N	Engine speed (rev/s)	**30**
V	Engine displacement (L)	**10.5**
C_d	Coefficient of aerodynamic drag	**0.9**
A	Frontal surface area (m2)	**10**
C_r	Coefficient of rolling resistance	**0.01**
η_{tf}	Vehicle drive train efficiency	**0.4**
η	Efficiency parameter for diesel engine	**0.9**
κ	Heating value of typical diesel fuel (kJ/g)	**44**

Traveling from A to B. What is the shortest path?



Davydov D & Velázquez-Martínez J.C. (2017).

What is the best in terms of Fuel Consumption?

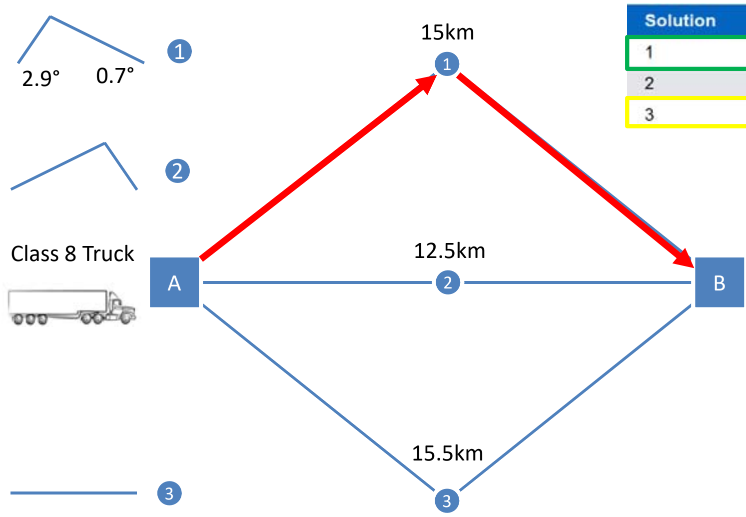


If $\theta = 0$ distance and fuel paths are **the same**

Solution	Fuel (L)
1	5.86
2	4.87
3	6.04

Davydov D & Velázquez-Martínez J.C. (2017).

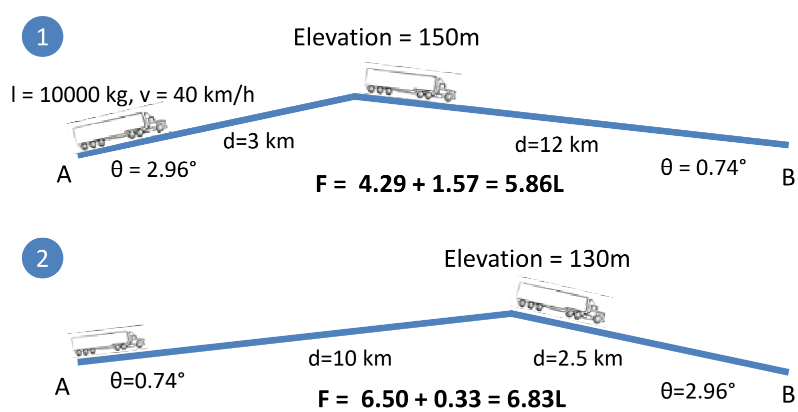
Let’s try again with the following topographies…



Solution	Fuel (L)
1	5.86
2	6.83
3	6.04

Davydov D & Velázquez-Martínez J.C. (2017).

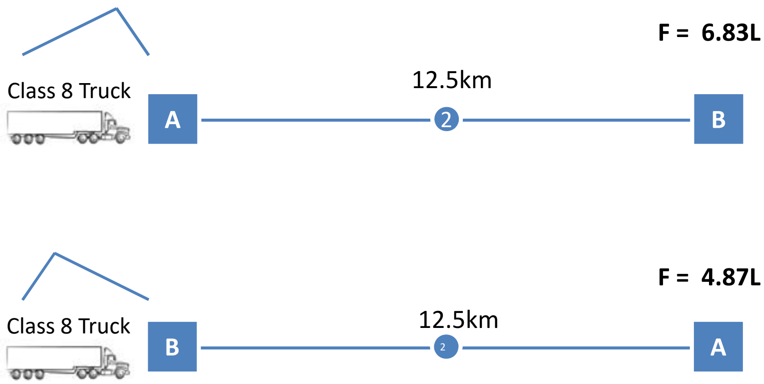
Fuel Consumption comparison



Solution	Fuel (L)	Distance (km)	Max Elevation (m)
1	**5.86**	15 (+20.0%)	150 (+15.3%)
2	6.83 (+16.5%)	**12.5**	**130**

Davydov D & Velázquez-Martínez J.C. (2017).

No Symmetry with Slopes



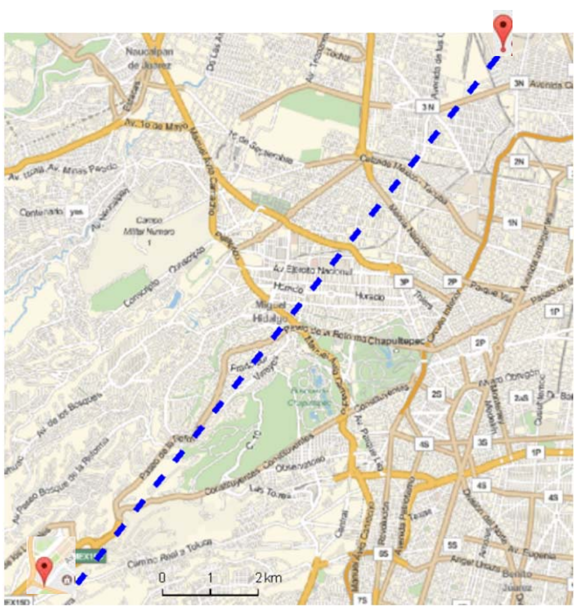
B to A requires **28.7%** less fuel than A to B

Davydov D & Velázquez-Martínez J.C. (2017).

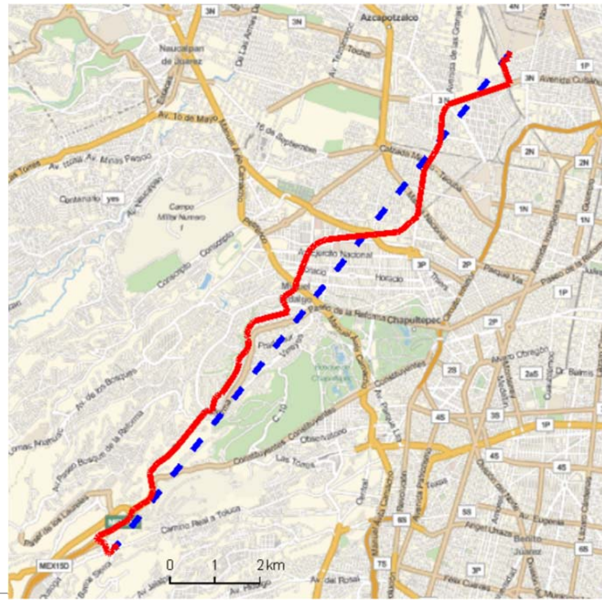
Preliminary illustrations for a CPG company in Mexico City

Case Study

- 1 Distribution center
- 21 medium-duty and 22 heavy-duty trucks
- ~8,000 customers
- ~6,500,000 km traveled yearly
- ~55 million of tons delivered yearly
- ~300,000 Lt of diesel consumed yearly
- ~4,000,000 MXN (~380,000 USD) spent on fuel yearly

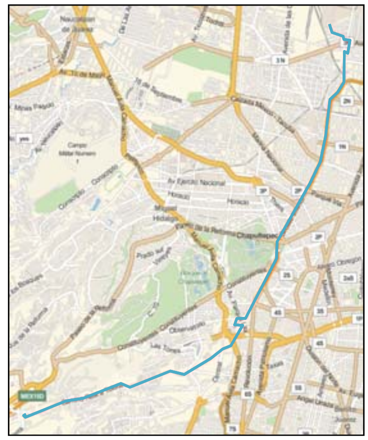


Shortest path



Fuel optimal path

Comparison

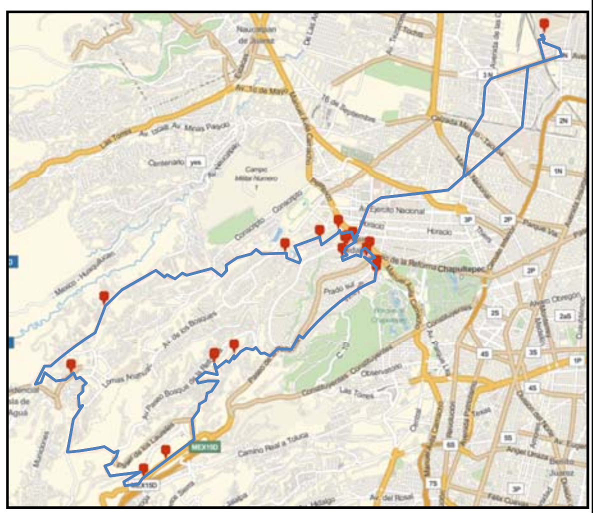


Solution	Distance (km)	Fuel Medium Duty (L)	Fuel Heavy Duty (L)
Distance Optimal	**17.23**	12.48 (+1.9%)	22.11 (+3.4%)
Fuel Optimal	17.47 (+1.4%)	**12.25**	**21.38**

Davydov D & Velázquez-Martínez J.C. (2017).

Routing example

- Medium-Duty Truck
- 19 customers
- Max elevation difference ~300m
- Overall demand ~2tons
- ~50 km in route
- 12.3 Liters of fuel



Davydov D & Velázquez-Martínez J.C. (2017).

Thanks!

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53