Chapter 2
Societal Requirements/Goals for a Sustainable Transportation System

Abstract This chapter defines our goals for a future transportation system in terms of the allowable greenhouse gas (GHG) emissions, fossil fuel consumption, and local air pollution to create a sustainable transportation system.

Every engineering project (in this case developing alternative transportation systems) needs to have measurable goals so that one can judge the success of a given design or designs.

Engineers typically include a set of *boundaries* to help to define the system that they are trying to evaluate. If they are designing a new car, the boundaries might encompass the entire car, with key inputs to the system being the quantity of gasoline or diesel fuel needed to travel 100 miles, and key outputs would include the gases exiting the tailpipe plus any fuel evaporation and particulate matter (PM) generated by applying the brakes and particles released due to tire wear on the road. But to analyze an entire transportation system, the boundaries must be expanded to include all inputs to the entire chain of manufacturing the vehicle and producing the fuel to power that vehicle. And the analysis must include all emissions from all vehicle manufacturing and fuel production operations as well as the actual emissions from the vehicle. One key example of the need for large boundaries is the greenhouse gas (GHG) emissions caused by driving a battery electric vehicle. The BEV itself emits no GHGs. But three quarters of all power plants in the USA use fossil fuels to generate electricity to charge car batteries. These power plants emit copious quantities of GHGs, primarily carbon dioxide (CO_2), the main GHG, and must be counted in the evaluation of the global impact of driving battery EVs; as more BEVs travel longer distances, GHG emissions from the electrical power plants will increase.

In other words, to properly evaluate the performance of a transportation system, we must consider civilization as a closed factory system that is supplied with three non-renewable fossil fuel tanks to supply most of its energy (petroleum, coal, and natural gas) and one renewable energy source (the sun) plus nuclear energy. This vast factory system is enclosed by a tent (called the atmosphere) that has a finite

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capacity to absorb waste products (primarily air pollution and GHG emissions). To continue sustainable operation, this factory must conserve the energy in its dwindling non-renewable fossil fuel tanks, and it must limit its waste streams to avoid poisoning the planet to such a degree that the health of future generations is put at grave risk.

This global factory system has four key sections: industrial, commercial, residential, and transportation. All these societal sections must conserve energy, water, and other material resources and minimize pollution to maintain a sustainable factory for future generations; however, this book focusses on the transportation sector, which consumes much of the world's energy and generates much of its pollution. In order to preserve anything close to our current standard of living in this global tent, we must set a goal of limiting at least three parameters of the transportation sector: GHG emissions, oil consumption, and local air pollution.[1]

2.1 Greenhouse Gas Emission Requirements

Transportation accounted for 34 % of all GHG emissions in the USA in 2012, and light-duty vehicles (LDVs) (cars and trucks) generated 61.5 % of those transportation GHGs,[2] so cars and light-duty trucks accounted for 21 % of all US GHGs [1]. Since GHGs (primarily CO_2) stay in the atmosphere for a century or more,[3] we must stop spewing these gases soon if we are to avoid the accumulation of excessive gases that could dramatically impact the future of our children and grandchildren. The pollution that we pour into the atmosphere today will still be plaguing our grandchildren and great-grandchildren 100 years from now.

The goal of the environmental community to avoid the most serious effects of climate change[4] is to decrease GHGs by a least 80 % below 1990 levels, ideally by 2050. In 2012, US transportation GHGs had increased by 18 % since 1990, so if transportation were required to cut GHGs 80 % below its 1990 level, that would require an 83 % reduction below 2012 levels. US industrial GHG emissions have already decreased by 10.8 % since 1990, so it may be difficult to cut industrial emissions further. It may also be more difficult to cut residential GHG emissions since the housing stock turns over slowly, so it may be necessary to require more

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[1]Clean water should probably be added to this list, since water is becoming a scarce resource in many parts of the world. All else being equal, we should choose transportation systems (including fuel production) that minimize the consumption of water.

[2]Light-duty trucks accounted for 18.4 % of all transportation GHGs in 2012 and light-duty cars 43.1 %.

[3]CO_2 has an atmospheric lifetime of approximately 100 years, while the other major GHGs such as methane (CH_4) and nitrous oxide (N_2O) have lifetimes of 12 and 298 years, respectively.

[4]The goal of the IPCC (Intergovernmental Panel on Climate Change) is to keep the global average temperature rise to no more than 2 °C (or 3.6 °F) above preindustrial levels.

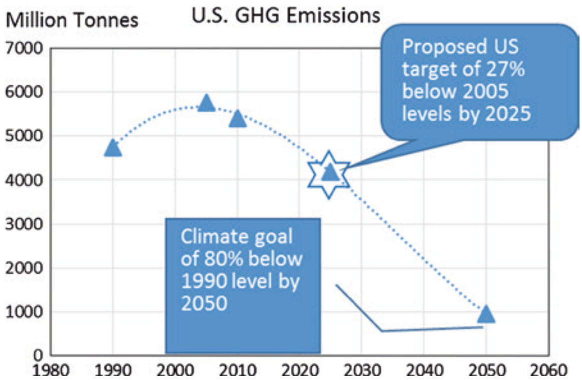


Fig. 2.1 US GHG emissions and the climate change goal of an 80 % reduction of GHGs by 2050 compared to the proposed goal of 26 % to 28 % below 2005 levels by 2025

than an 80–83 % reduction for transportation to accommodate other sectors missing the 80 % reduction goal.

For example, in a detailed analysis of GHG emissions in the European Union, McKinsey & Company concluded that road transportation would have to be *reduced by* 95 % below 1990 levels, after taking into account the likely reductions possible in other sectors of the EU economy [2]. For example, they concluded that air and sea transports could only be reduced by 50 % and industrial GHGs by 40 % and agriculture by 20 %, leaving a larger burden of 95 % reduction for road transport.

Assuming that medium- and heavy-duty trucks are included in "road transport" that accounts for 20 % of all US GHGs, then one could argue that LDVs would have to be reduced by more than 95 % below 1990 levels to reach a total reduction of 95 % for all road transport.[5]

On a trip to China on November 12, 2014, President Obama and Chinese President Xi agreed to set a goal of reducing GHGs by 26–28 % below 2005 emission levels by 2025 [3]. This is a worthy step in the right direction, but is only 11.5 % below the 1990 US GHG emission level, which might seem far short of the 80 % reduction goal. However, this 11.5 % reduction by 2025 does fall on the glide slope[6] toward the climate change community goal of an 80 % reduction below 1990 levels by 2050 as shown in Fig. 2.1, even though the US 2005 GHG level was 21 % above 1990 GHG emission levels.

We conclude that the GHG reduction goal for LDVs should be at least an 80 % reduction and preferably a 95 % reduction below 1990 levels, preferably by 2050, but at least by the second half of the twenty-first century.

[5]This assumes that it will be more difficult to reduce GHGs from medium- and heavy-duty trucks than from light-duty vehicles, which would certainly be true for battery EVs, but not necessarily for fuel cell EVs. To the degree that hydrogen and fuel cells could also power heavy trucks, and air and sea transports, the GHG reduction targets for light-duty vehicles might be reduced.

[6]A cubic polynomial fit to the data.

2.2 Dependence on Finite Fossil Fuels

Some US citizens may becoming less anxious about petroleum dependence on nations from OPEC with the precipitous drop in oil prices in 2014 and 2015 coupled with new oil production in the USA through fracking; but OPEC nations still have more than 72 % of proved global petroleum reserves (see Fig. 2.6) and could therefore pose a significant global threat in some future crisis unless developed nations reduce our consumption of petroleum. Most citizens think of motor vehicles when they consider the world's voracious and growing appetite for petroleum. Transportation accounted for 72 % of all petroleum consumption in the USA in 2013 as shown in Fig. 2.2 [4].

Of this transportation amount, LDVs accounted for 58.6 % [5] (see Fig. 2.3), so that LDVs consumed 42.4 % of all US petroleum in 2013.

But petroleum use is much more pervasive than just in transportation. As UCLA Professor Jared Diamond hypothesized [6] when he explored the reasons why modern civilization grew and flourished in Asia and Europe (and subsequently in the USA), but not in places that he analyzed like Papua New Guinea,

Fig. 2.2 US oil consumption (quads) by sector

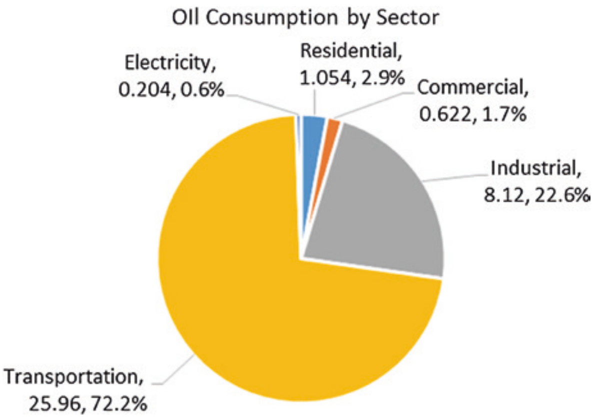
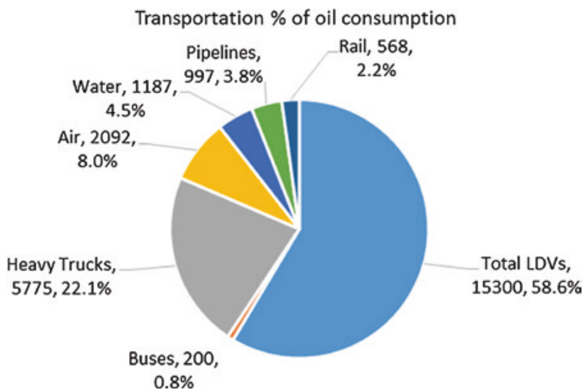


Fig. 2.3 Transportation sector % oil consumption by mode of travel (trillion BTUs) for 2013



where natives in the highlands still live in a prehistory "hunter-gatherer culture," modern civilizations developed where two key resources were available or could be successfully imported: domesticated, high-yield crops such as wheat, barley, and rice and domesticated animals such as pigs, sheep, cattle, and horses (and particularly cattle and horses that provided mechanical force to augment human farm labor). These two ingredients allowed ancient hunter-gatherer peoples in the Fertile Crescent (Mesopotamia and now modern Iran and Iraq) 12,000 years ago to settle down and form the first cities since farmers could grow enough food to support large groups of people. Prof Diamond concluded that the people he met in Papua New Guinea were just as smart and probably more resourceful and hard-working than American or European citizens, but they lack the climate that could support high-yield crops or horses or cattle to help with farming chores.

When the first Europeans brought cereal grains and horses to the USA, and American farmers moved to the fertile Midwest of the USA, the essential ingredients for a thriving civilization were planted. The advent of the steam engine and later the internal combustion engine allowed farmers to improve their yields many times over compared to relying strictly on horses to power farm equipment. While the end result is striking in terms of food production capacity, food production is now highly dependent on petroleum for everything from fertilizers, pesticides, herbicides, and fossil fuels for farm equipment, and gasoline and diesel fuel to transport farm produce to the food processing plant, and still more petroleum products to bring the finished food products to the supermarket. In 1994, one study estimated that growing food consumed *400 gal of petroleum to produce the food for one American* [7]. This amount of gasoline would propel a vehicle with 30 miles/gal fuel economy 12,000 miles/per year.

So what should be our goal for reduction of oil consumption? US politicians of all stripes have called for "energy independence" for many decades, setting the goal of eliminating the importation of *any* foreign energy supplies.[7] While this makes great campaign rhetoric in terms of offering the promise of cutting the military costs for defending our oil lifeline to the volatile Middle East and offering the chimera of reduced gasoline prices at the pump, in reality the goal of energy independence is probably not attainable in the foreseeable future and would probably not yield the promised advantages. Energy independence will most likely not be achievable for many decades, if ever, since the USA would have to greatly expand the recent surge in shale oil production and probably develop huge quantities of alternative energy sources such as wind, solar, biomass, coal gasification, or possibly nuclear fusion. Ironically, any of these alternative energy sources would most likely require a huge surge in oil consumption to manufacture and install these new systems and the investments of tens of billions of dollars by some combination of industry and government to build new infrastructure. In terms of reduced gasoline prices (or alternative fuels such as electricity, hydrogen or biofuels), most

[7]Denmark set a goal of eliminating all fossil fuel energy use in transportation by 2050, relying primarily on hydrogen-powered vehicles [8].

of these new energy sources will be more expensive than gasoline per unit of energy, at least in the short term.[8]

But even if the USA were somehow able to achieve energy independence, we live in a global economy, as dramatically illustrated by the impact of the European debt crisis on US stock markets in the deep recession in the 2010–2011 time period. Unless all nations could duplicate our energy independence feat, the world would still depend on oil coming from the Persian Gulf, and OPEC would still be in a position to disrupt the global economy. So we would still be gravely concerned about any unrest in the Middle East that could disrupt the flow of oil to our friends and allies.

Society has not established a specific target for reducing petroleum consumption analogous to the 80 % reduction goal for GHGs, but one goal might be to reduce oil consumption such that in some future emergency, the USA could supply all of its petroleum needs from non-OPEC nations and, preferably, from friendly countries on the American continent.

Fortunately, these goals seem attainable. In 2005, US oil imports peaked at 2.52 billion barrels of oil. With the Great Recession of 2008, oil imports dropped 14 % to 2.48 billion barrels [9].

Many Americans may be under the impression that most of our oil is imported from the 12 OPEC nations,[9] with much of that oil coming from the Middle East.

However, Canada was our largest supplier of oil in 2013 (33.5 %), followed by Mexico at 9.8 % and the rest of Central and South America at 16.4 %, for 2013. Over 50 % of our oil imports came from the American continent. Only 39.7 % of our imports came from OPEC nations, as shown in Fig. 2.4 [10]. As shown in Fig. 2.5, since 2008, the percentage of oil imported from countries on the American continent has been steadily increasing compared to oil imported from OPEC countries, while the percentage imported from the Persian Gulf has been holding relatively steady near 20 %.

While US production is rising due to shale oil formations, the OPEC nations still have approximately 72.2 % of all proved oil reserves as summarized in Fig. 2.6, while North America has only 13.2 % of proved reserves; although unconventional oil exploration may help to alleviate this imbalance, OPEC will undoubtedly have a large influence on world oil supply for many decades. US oil production peaked in 1970 at 3.52 billion barrels and has been steadily declining

[8]Grid electricity currently costs less to power a battery electric vehicle in many parts of the nation now using fossil fuels, but if society imposed carbon standards and required the generation of clean electricity independent of fossil fuels, then electricity costs would be much higher; we show in Chap. 13 that hydrogen made from waste used in a fuel cell EV could be priced at a cost that is 10 % *less* than gasoline per mile driven in a regular car; but hydrogen may cost more than gasoline per mile initially until mass production of hydrogen fueling stations brings their prices down.

[9]OPEC = Organization of the Petroleum Exporting Countries which includes 12 nations (six in the Middle East—Iran, Iraq, Kuwait, Qatar, the United Arab Emirates, and Saudi Arabia); four from Africa (Libya, Algeria, Angola, and Nigeria), and two from South America (Ecuador and Venezuela).

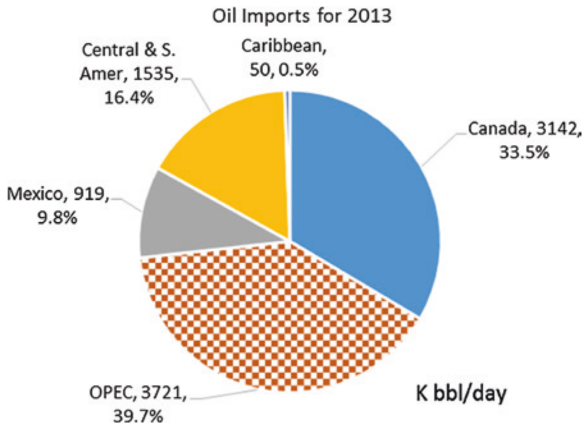


Fig. 2.4 US oil imports for 2013 in thousands of barrels per day

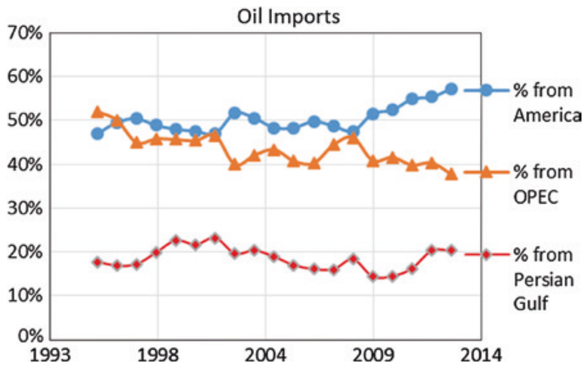


Fig. 2.5 Percentage sources of US oil imports over the last 8 years

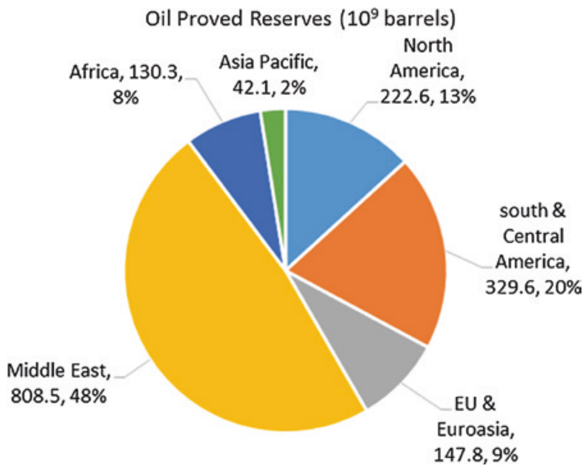


Fig. 2.6 Proved oil resources (trillion barrels) by region

Table 2.1 Oil available for LDV transportation under two oil import constraints for 2013: oil imported only from non-OPEC nations and oil only from the American continent

Import sources=>	Non-OPEC billion bbl/year	Americas only
2013 US production	2.72	2.72
Imports	2.24	2.05
Total oil available	4.9567	4.76252
Minus non-transport use	1.80	1.80
Available for transport	3.15	2.96
Minus non-LDV transport	1.87	1.87
Remainder for LDV transport	1.29	1.10

until hitting a low of 1.83 billion barrels in 2008; US oil production has rebounded since 2008 due to economic recovery and the discoveries of shale oil, reaching 2.72 billion barrels in 2013 [11].

The goals of importing all oil from "friendly" nations in the Americas[10] or only from non-OPEC nations are summarized in Table 2.1, based on 2013 data. In 2013, the USA imported 2.24 billion barrels from non-OPEC nations. Combining this with the US production of 2.72 billion bbl/year yields 4.96 billion bbls of oil available. Deducting the 1.8 billion bbl used for non-transportation needs leaves 3.15 billion bbl for all transportation. Subtracting off the 1.87 billion bbls used for other transportation needs (heavy trucks, trains, planes, etc.) leaves a residual of 1.29 billion bbl/year for LDVs. For the case of oil imported only from the American continent, the same tabulation indicates that only 1.1 billion bbl/year would be available to power LDVs.

We therefore set the goal of reducing LDV oil consumption to the range between 1.1 and 1.29 billion bbl/year, which would provide sufficient oil in some future energy crisis[11] without relying on OPEC or other nations outside the American continent. Note that these two goals are based on 2013 oil production, imports, and vehicle consumption. All three of these elements will undoubtedly change in the future, which will affect these goals. We assume that US oil production will rise, as will oil from other American and non-OPEC nations, which would increase the oil available for transportation.

2.3 Local Air Pollution

The twin threats of climate change and dwindling supplies of fossil fuels that reside in dangerous parts of the world have dominated the recent calls for developing and deploying cleaner cars in the developed nations, but local air pollution

[10]Excluding Venezuela, a founding member of OPEC.

[11]Even then, unless other nations of the world made similar reductions in their petroleum consumption, OPEC would still exert extraordinary influence in such a crisis.

remains a major threat to citizen's health in many parts of the world. Urban air pollution for some pollutants exceeded twice the World Health Organization limits in 2011 in seven "megacities" around the world[12] (a megacity is defined as having more than 10 million inhabitants). Mexico City was the most polluted city with more than twice the WHO-recommended safe levels of sulfur dioxide (SO_2), suspended particulate matter (SPM), carbon monoxide (CO), and ground-level ozone (O_3) [12].

Reducing urban air pollution in major cities around the world will require substantial reductions in motor vehicle emissions. Hence, the development and successful deployment of affordable clean vehicles in the USA will most likely be essential to reducing global urban air pollution.

Local air pollution is also still a major concern in some parts of the USA. Urban air pollution has been declining, but many areas of the USA still exceed the EPA limits for the six major "criteria pollutants"[13] covered by the Clean Air Act, as shown in Fig. 2.7. These criteria pollutants create significant health hazards for urban citizens and can also adversely impact crop growth in rural areas. Most of the non-attainment counties are in California, but criteria pollutants exceed the EPA standards in the Dallas/Fort Worth and Houston areas in Texas, and in many urban areas on the East Coast. Areas east of Cleveland and Pittsburg exceed the limits for 6 or 7 pollutants (red, pink or purple in Fig. 2.7).

While all-electric vehicles such as battery EVs and fuel cell EVs do not produce any significant criteria pollutants from the vehicles,[14] some pollutants are emitted in the process of producing the fuels for these vehicles (electricity and hydrogen).

The other major alternative vehicles such as hybrid electric vehicles and plug-in hybrids do have small gasoline- or diesel-powered internal combustion engines in the vehicles that emit significant criteria pollutants from their tailpipes, so it will be difficult to reduce air pollution if they continue to be part of the vehicle fleet.

The goal for the reduction of local air pollution should be to reach the EPA standards [13] for criteria pollutants in all regions of the country and for all cities of the world to achieve the World Health Organization standards for urban air pollution.

[12]Mexico City, Beijing, Cairo, Jakarta, Los Angeles, Sao Paulo, and Moscow [14].

[13]PM including two sizes: PM-2.5 and PM-10, referring to the size of the particles in microns, low-level ozone, CO, Sulfur oxides, Nitrogen oxides and lead.

[14]Actually, electric vehicles do generate particulate matter (PM) from brake linings during braking, and from tire wear on the roads. So the California "Zero Emission Vehicle" (ZEV) rating really only applies to tailpipe emissions and not to tire and brake wear.

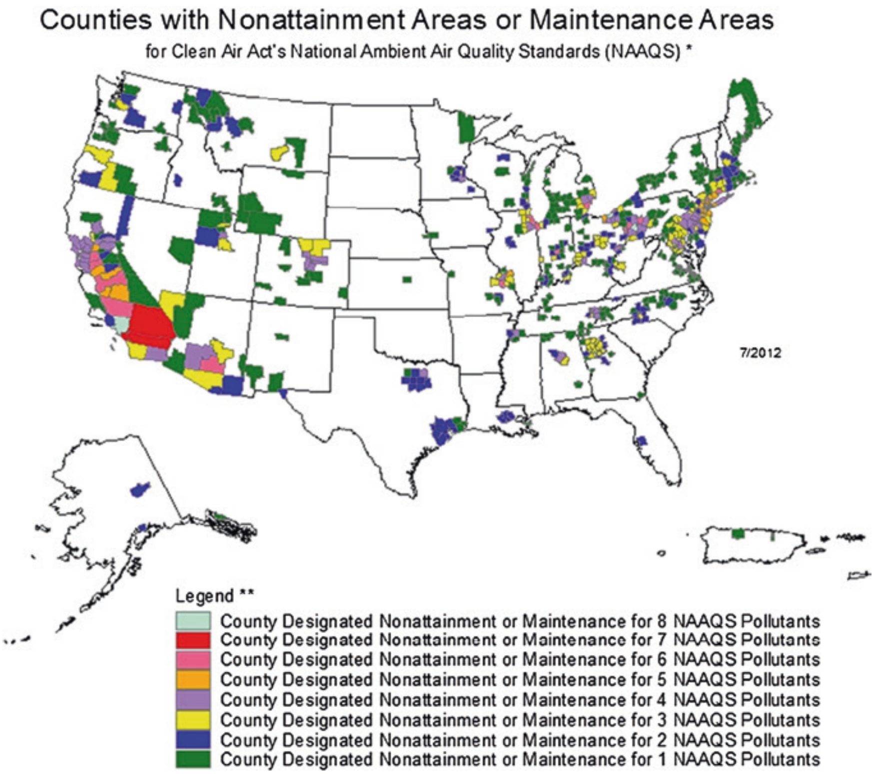


Fig. 2.7 Counties in the USA that did not meet the EPA standards for at least one urban air pollutant (*NAAQS* National Ambient Air Quality Standards for the six "criteria pollutants" specified in the Clean Air Act)

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