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Tailpipe greenhouse gas emissions from tank trucks transporting raw milk from farms to processing plants

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ABSTRACT

An analysis of greenhouse gas emissions (carbon dioxide equivalents, CO_2e) was conducted from 2007 databases for 211,216 round trips of tank trucks that delivered raw milk from farms to processing plants in the United States of America. The total amount of milk was 4.81×10^9 kg, or about 17.4% of the 2007 total USA production for use as fluid milk products. Average round trip distance was 850 km resulting in tailpipe emissions of 0.050 kg CO_2e kg^{-1} milk delivered or 0.071 kg CO_2e kg^{-1} milk consumed representing 3.5% of the total greenhouse gas emissions for fluid milk consumed. Based on this we estimate the total emissions for fluid milk delivery from farm to processor in the US at 1.3×10^9 kg CO_2e y^{-1}. Some overall reduction in total delivery distance could be realized by realigning farm-to-processor relationships, especially in regions where farms are equally distant from multiple processors.

1. Introduction

Contributions to the embodied greenhouse gas emissions of fluid milk include those upstream from the farm (fertilizer production, feed production, water production, and the transportation of all of these to the farm), operations at the farm, transportation of raw milk from farm to processing plant, processing of raw milk to a consumable fluid milk, distribution of fluid milk to retailers, storage and handling at the distributor, transportation by the consumer from retailer to home, and end losses due to spoilage and wastage. The purpose of this paper is to estimate the greenhouse gas emissions (carbon dioxide equivalents, CO_2e) from the transportation of raw milk from farms to processors in terms of kg CO_2e kg^{-1} milk delivered. The milk considered in this project ended up as fluid milk products – plain and flavored varieties of whole, low fat, and skim, while milk shipped to cheese production was excluded. Since liquid milk is transported almost exclusively by truck in the United States of America, this was the only means considered. Rail transport in the USA is used only for processed dairy products such as ice cream, yogurt, and canned milk that are not highly perishable and does not have to be delivered on a strict schedule (Ortego, 1979). Typically, raw milk is delivered by insulated unrefrigerated tank trucks from one or more farms to a processor. A truck will make a round trip, visiting farms along its route, picking up milk at each, and delivering the combined load to the processor. Tank capacities range from a few hundred to about 34,100 L with 22,700 L (23,400 kg) being the most common.

2. Material and methods

Access was obtained to two proprietary databases of farm-to-processor delivery information for calendar 2007 representing 4.81×10^9 kg, or 17.4% of the 27.7×10^9 kg of total fluid milk produced in the USA in 2007 (Wisconsin Milk Marketing Board, 2012). Both databases had their origin in automated data logging hardware on the tank trucks that either transmitted or dumped the truck's activity log at the end of each day. A very large amount of information was available from these, including truck and driver identification, length of breaks, and average speed, but the only items of interest for this study were those associated with individual round trip distances and delivery amounts. Extraction of the relevant data required considerable filtering to correlate the information and to remove absent or invalid records from over a third of a million rows of comma-separated values (csv) data. Database 1 was particularly labor-intensive in this way, but both were much too large for any manual manipulation. All data filtering, correlating, and analysis was done using code written in MatLab that would read directly from the csv files, process the

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extracted data according to a set of validation rules, and calculate the results.

Database 1 provided the latitude and longitude for the processing plant and for each associated farm for a given trip but not the actual driving distances. Furthermore, the organization providing this data was engaged in “load sharing” whereby trucks would on some trips pick up milk from farms associated with other organizations for delivery to the same processor. This is a common practice in the dairy industry to increase transportation efficiency and is more frequently used by smaller farms that, even as a local group, cannot fill up an entire truck. For load shared trips the amounts of the Database 1 organization’s milk loaded at the farms were recorded along with the farm’s locations but there are no records of the pickup locations or amounts for the load shared milk belonging to other organizations. Therefore, trips with load sharing could not be used in this analysis because the total round trip length could not be calculated.

To filter out the load shared trips, only those milk deliveries to processors where the reported delivery weight equaled that expected from full trucks were captured since these would be only from the organization’s farms. For instance, the database might indicate that a truck on a certain trip returned with 6900 L of milk. This amount does not match the full capacity of any common tank truck and is much smaller than the average delivery; therefore load sharing must have occurred on this trip. The truck probably arrived at the processor full of milk, but some unknown amount was from load sharing. We decided to include only those trips that delivered between 20,800 and 23,900 L (21,500–24,600 kg) to be reasonably sure that all of the pickup points and milk amounts in the trip had been recorded. We were looking for full 22,700 L trucks, by far the most common capacity. About 40% of the total trips met this criterion and had a full set of non-zero listed distances and delivery amounts resulting in 141,617 useful round trips, most of which still visited multiple farms. On average 3.1 farms were visited per trip in the parts of Database 1used in this study. Since load sharing is more common with smaller farms, exclusion of this data might impart some upward bias in the reported average distances. The organization providing Database 2 does not load-share so no such filtering was necessary there and the results were similar to those from Database 1 indicating that load sharing did not markedly affect the overall greenhouse gas emissions per kg milk delivered.

Database 1 did not provide driving distances for each round trip, but it did list the latitude and longitude of each farm in the trip in the order visited as well as for the processor to which the milk from that trip was delivered. Driving distances were estimated by submitting the individual legs from each trip to Google Maps online service. There were over 300,000 individual legs in Database 1 but this number was reduced to 29,934 since most legs were repeated continuously throughout the year. A script was written to automatically submit a few thousand a day to Google Maps using their option of finding the fastest route (rather than the shortest distance) to model the logic assumed to be used by a truck driver. The resulting collection of Google Maps distances for each of the possible legs was used as a lookup table to obtain the driving distances for each of the 141,617 Database 1 round trips used in this study.

This collection of driving legs could be used for other transportation studies as well where distances and times need to be estimated for driving between two locations. Fig. 1 shows the ratio of the shortest-time Google Maps driving distance to the straight line great circle distance as a function of the latter for the 29,934 legs reported in Database 1. As expected, the driving distances are very scattered for shorter trips but tend to converge to a fairly constant value of 15–20% extra for cross-country distances. A fifth-order polynomial was fitted to a moving average of these points to provide an algebraic relationship for calculating the distance ratio from the straight line length of the trip in km; the equation is shown in Fig. 1 and is plotted as a gray line. This equation was not used in this study because we knew the individual farm and processor locations and could get the actual driving distances directly for each leg. Google Maps also gives estimated driving times and, although also not used in this study, the driving time

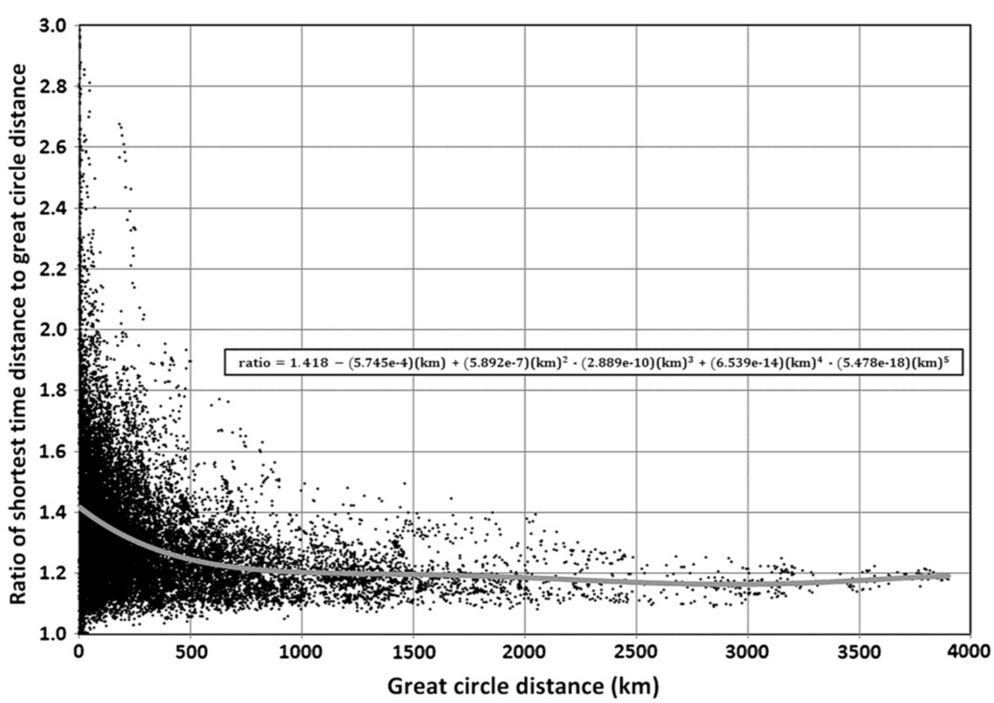

Fig. 1. Ratio of driving distance from Google Maps to the great circle distance for 29,934 unique trip legs used in this project. The polynomial fit is shown as the solid gray line.

versus straight line distances were captured and are shown in Fig. 2.

Database 2 was much more straightforward since it contained the actual driving distances, the organization did not load share and, unlike Database 1, every trip was out and back to one single farm. Since the delivered weights were all near the equivalent value of 23,400 kg, all trucks in this database were assumed to have a capacity of 22,700 L. We removed about 20% of the records due to distance or delivery amount data that was either zero or an impossible value leaving 69,599 useful trips.

For both sets of data it was assumed that the empty truck was stored at the processor when not in use. In reality, the private hauler structure of the dairy industry likely results in trucks that are stored at independent depots but, in calculating round-trip distances, it is assumed that the overnight location has little impact on the overall route distance.

3. Results and discussion

3.1. Delivery distances from farm to processor

Figs. 3 and 4 are histograms of the round-trip distances from the two databases. The overall distribution of round-trip delivery distances appears roughly lognormal, and the averages for the two data sources are 887 and 774 km. The spiked nature of the data is due to some routes being repeated numerous times between farms or groups of farms and processors. Fig. 5 shows typical results for Nebraska, a state that does not import as much milk as Louisiana, shown in Fig. 6. The clumps of distances beyond 800 km for Louisiana, and states like it, are trips to distant groups of farms in areas of the USA that have surplus supply available for deficit markets. Spreading of these distance groups is often due to variations in the pick-up patterns to these groups of distant farms. All milk marketing organizations strive to shorten their total driving distance not necessarily out of concern for greenhouse gas emissions, but to minimize their expenses, and it is rare for a truck to be delivered to the processor less than full. The long distances seen in the Louisiana data are an extreme case to illustrate the point that some milk marketing might extend out over a thousand km to deliver milk to deficit markets. These seemingly extreme distances are sometimes necessary to move milk from areas where the average dairy cow-to-people ratio is high, such as the Midwest, to areas where this ratio is low, such as Louisiana and Florida.

3.2. Carbon emissions per km delivery distance

Virtually all milk transport from farm to processor in the USA is accomplished using class 8 trucks, which have a loaded weight exceeding 15,000 kg or, in Europe, class N3 that are those in excess of 12,000 kg. We are sure that these are the only types of trucks present in this study because we only considered milk deliveries exceeding 21,500 kg for reasons explained above. Diesel fuel is universally used in these heavy trucks due to its higher efficiency and simpler engine design compared with those that use gasoline, so this was the only fuel considered. In heavy trucks such as these, only about 6.5% of the energy in each liter of diesel fuel is used to move the cargo and 4.5% is used to move the truck and cargo container. The remaining 89% is lost as follows: 56% to thermodynamic effects in the engine, 19% to overcome aerodynamic forces, 12% due to idling, 11% to tire rolling resistance, and 2% to driveline and transmission drag. At 105 km h^{-1}, two thirds of the horsepower created by the engine is used to overcome aerodynamic drag (Osborn & Ramroth, 2007). Rolling resistance of the tires and acceleration to constant speed are the only loss mechanisms that are dependent on the mass of cargo being carried, and these are a minor contributor to fuel usage. Hence, the truck's fuel km L^{-1} values are only a weak function of the amount of milk on board and, by extension, whether they are going to the farm empty or coming back full.

The median service life for heavy trucks is 20–25 years (Davis, Diegel, & Boundy, 2008a) so we considered fuel efficiencies from this time period. From 1990 to 2005, the efficiencies for heavy

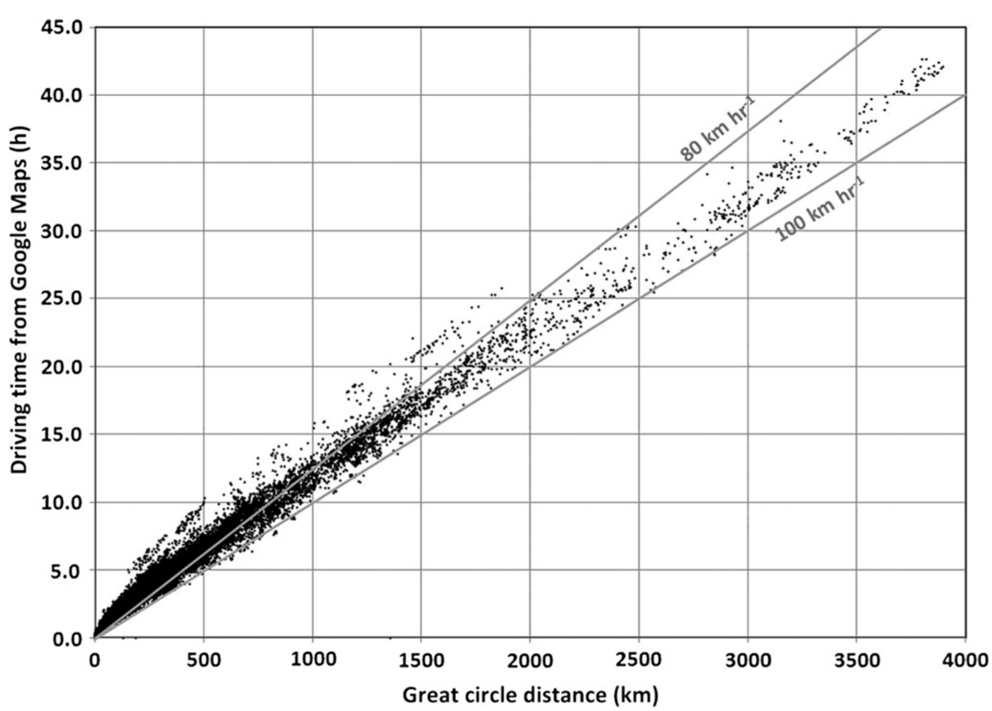

Fig. 2. Estimated driving times from Google Maps using the fastest route option for the same 29,934 unique trip legs in Fig. 1.

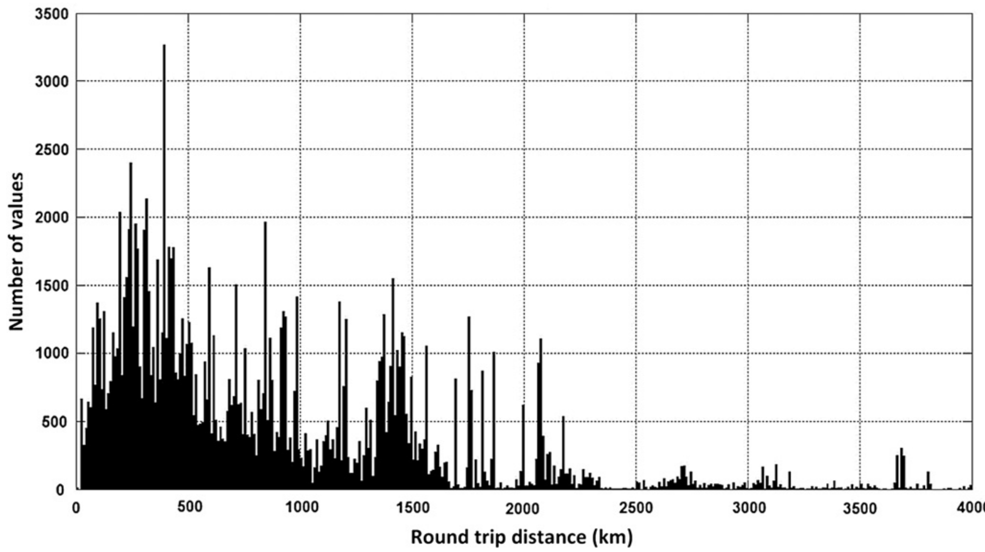

Fig. 3. Histogram of round-trip distance for 141,617 raw milk deliveries in 2007 from farm to processor taken from Database 1. The average is 887 km.

trucks was 2.2–2.5 km L^{-1} (Davis, Diegel, & Boundy, 2008b) and, from 1992 to 2002, 2.3–2.5 km L^{-1} (US Census Bureau, 2004). For this study we used an averaged value of 2.4 km L^{-1}. The emissions from combusted diesel fuel is 2.67 kg CO_2e L^{-1} (US Environmental Protection Agency, 2005), so the tailpipe emissions are 1.11 kg CO_2e km^{-1}. Since the trucks are not refrigerated the only greenhouse gas emission considered was CO_2 in the exhaust. Pre-combustion losses for diesel fuel were taken into account. These have been estimated at 4–8% for extraction, 1–2% for shipment, 9–13% for refining, and 1% for distribution for a total of between 15 and 25% (US Environmental Protection Agency, 2006). We used an averaged value of 20%. Combined with the tailpipe emissions, the total becomes 1.33 kg CO_2e km^{-1} and this was the value used in this study. We did not include contributions from the entire life cycle of the truck, but these have been estimated at 76% for burned fuel, 5% for pre-combustion losses (the two contributions we did include), 11% for vehicle manufacture and disposal, 8% for “infrastructure” (Facanha & Horvath, 2007). If all of these were taken into account the emission factor would be 1.63 CO_2e km^{-1}.

3.3. Greenhouse gas emissions due to milk delivery from farm to processor

Table 1 shows the emissions from the combined databases broken down by USA dairy production regions and summed into a total for this study. The data are organized around regions where the processor is located since one processor might take milk from farms in other regions. Fig. 7 shows the boundaries for these regions. The overall emissions are 0.050 kg CO_2e per kg milk delivered but are higher per kg milk consumed due to losses at the retail and the consumer level. These losses have been estimated as 12% at retail and 20% at consumption, equivalent to 29.6% loss of all milk produced prior to it being consumed (US Department of Agriculture Economic Research Service, 2010). Thus there are 1.42 kg of milk delivered from the farm per kg consumed. Correcting the emissions for consumption gives 0.071 kg CO_2e per kg milk consumed. Thoma et al. (2012) found that the overall emissions were 2.05 kg CO_2e per kg milk consumed. Dividing this into the farm-to-processor transportation burden indicates that this

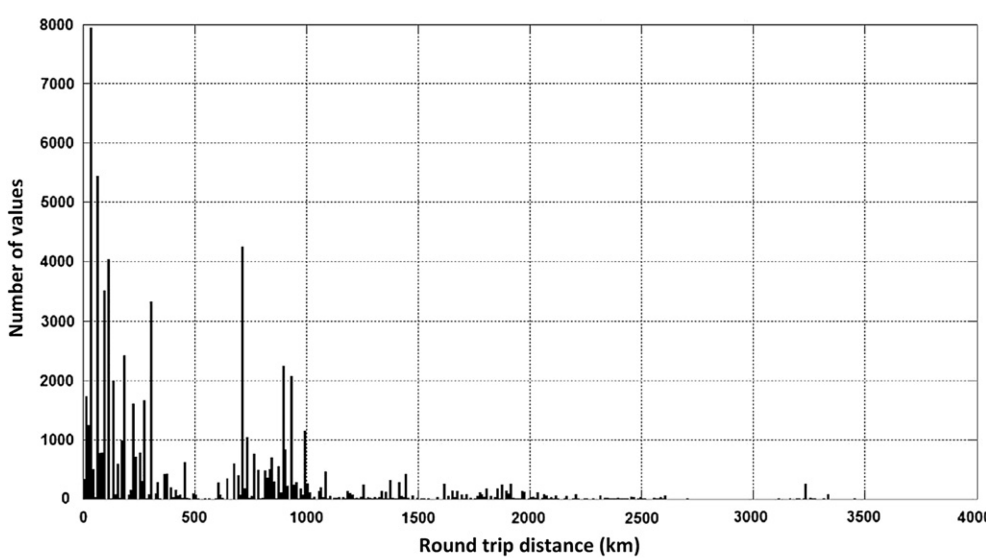

Fig. 4. Histogram of round-trip distance for 69,599 raw milk deliveries in 2007 from farm to processor taken from Database 2. Note that the vertical scale is twice that of Fig. 3. The average is 774 km.

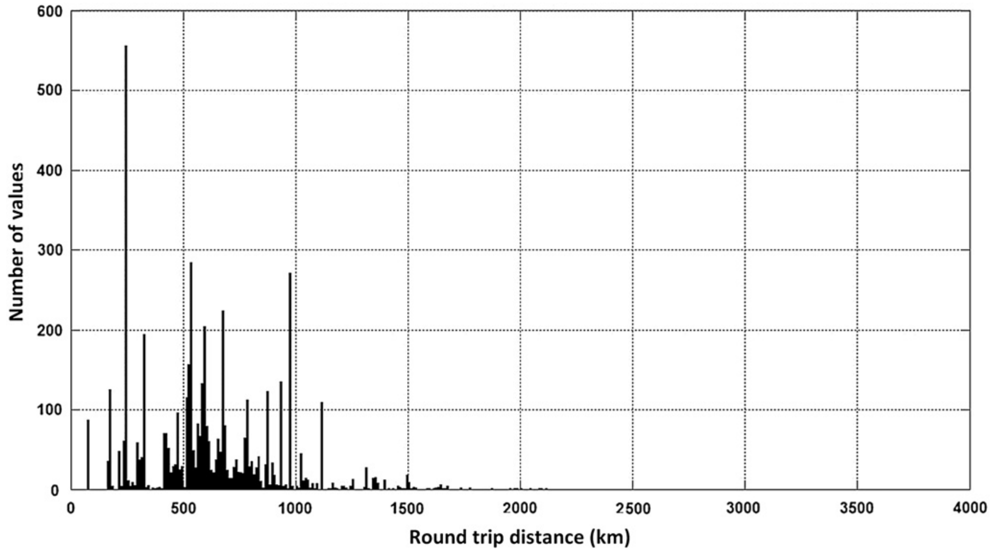

Fig. 5. Histogram of round-trip distance for 5054 raw milk deliveries to processors in Nebraska in 2007 from farm to processor.

portion amounts to 3.5% of the total greenhouse gas emission for milk consumed.

The total amount of delivered milk represented in these two databases is 4.81×10^9 kg, or 17.4% of the 27.7×10^9 kg of total fluid milk produced in the USA in 2007 (Wisconsin Milk Marketing Board, 2012). Taking the average value from this study of 0.050 kg CO_2e kg^{-1} delivered milk as representative and multiplying by 27.7×10^9 kg of fluid milk in the USA gives 1.4×10^9 kg of CO_2e emissions from the USA farm-to-processor milk delivery system. By comparison, all USA transportation sources carrying people and freight accounted for 1.86×10^{12} kg CO_2e in 2006, approximately 28% of all greenhouse gas emissions in the USA (US Environmental Protection Agency, 2008a). Emissions from all trucks heavier than 3860 kg was 365×10^9 kg in 2006 (US Environmental Protection Agency, 2008a), and the emissions from the entire agriculture economic sector were 534×10^9 kg (US Environmental Protection Agency, 2008b).

3.4. Possibilities for delivery distance reduction

As described above, Fig. 3 is a histogram of round-trip delivery distances between processors and farms from the first database and had an average round-trip distance of 887 km. This database contained 132 separate processing plants that were served by 7664 farms for an average of 58 farms per processor. Due to the evolution of relationships between specific farms and processors, the farms that provide raw milk may not necessarily be the closest ones resulting in a higher than optimal total delivery distance. A program was written to estimate this lowest-possible round-trip delivery distance for each processor based on the location of all processors and farms in the database. The equation shown in Fig. 1 was used to convert straight line distances to actual driving distances.

Total round-trip distances were calculated two ways to show the effects of competition for the closest farms. The first method was to find the round-trip distance to the closest 58 farms for each of the

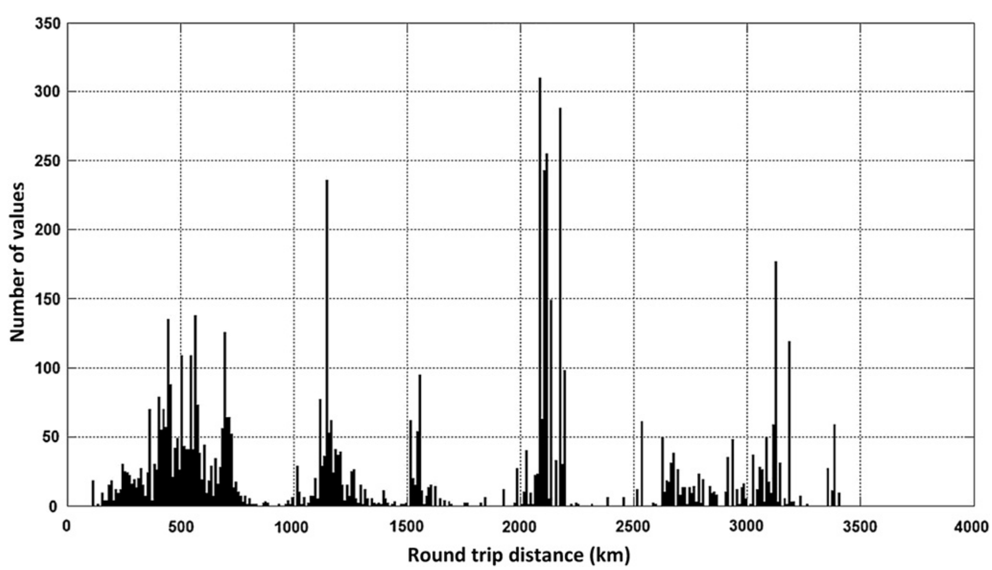

Fig. 6. Histogram of round-trip distance for 6514 raw milk deliveries to processors in Louisiana in 2007 from farm to processor.

Table 1
Results sorted by dairy region.[a]

Region	Number of trips	Number of producers	Distance driven (km)	Amount milk delivered to plants (kg)	Average producers per trip	Average distance per trip (km)	Average amount milk delivered per trip (kg)	kg CO_2e kg^{-1} milk delivered
1	2304	8878	2,839,294	52,798,676	3.9	1232	22,916	0.071
2	37,190	111,158	57,244,193	840,860,191	3.0	1539	22,610	0.090
3	20,798	63,078	11,072,783	474,260,596	3.0	532	22,803	0.031
4	141,338	192,306	103,901,064	3,200,986,144	1.4	735	22,648	0.043
5	9586	16,857	4,439,062	226,797,121	1.8	463	23,659	0.026
Total	211,216	392,277	179,496,396	4,795,702,729				
Average					1.9	850	22,705	0.050

[a] Regions are as defined in Fig. 7.

132 processors with no regard to whether or not any farms are counted more than once. The round-trip distance to the closest farm was averaged for each processor as was the distance to the second and so on, resulting in 58 average distances, each larger than the previous, shown as black bars in Fig. 8. These progressively longer distances are the average round-trips if each processor were able to take milk from its 58 closest farms. The average trip for this scenario for each processor would be 299 km assuming all farms are visited individually and the same number of times, and would require 17,300 km to visit each farm once with individual trips.

However, the actual minimum possible average distance will be greater than this because nearby processors would be in competition for the closest farms and would have to reach out further to collect 58 each. This is the case if each farm serves only one processor, which is the most common relationship. For this scenario, the program determined the one closest farm to a processor, then removed that farm from further consideration since they are then attached to a processor. This process was repeated so that each processor could, in turn, select the closest remaining farm for their own. In this way a network of farm-to-processor relationships could be determined so that each farm served only one processor and the overall distances were minimized. These are shown as the gray bars in Fig. 8 and, as expected, are all longer than the case where individual relationships are not considered. The differences are increased for longer distances since there will be more overlap between the ranges that individual processors will be reaching out for farms. The average round-trip distance is also considerably longer at 734 km, and 42,600 km is required to visit each farm once and individually. This is slightly shorter than the actual average in the database of 887 km for Database 1 from Fig. 3.

Increasing the capacity of each processing plant, thereby decreasing the total number of processors, would reduce competition for the closest farms but is more than offset by the larger number and lengths of required routes per plant. If 25% of the processors in Database 1 are chosen at random to be closed, reducing the number from 132 to 99, with a concurrent increase in processing capacity of each remaining processor by 33.3% to maintain the same total processing capacity, each processor would then be served by 77 farms instead of 58. For this case a total of 57,300 km is required to visit each farm individually once. While this would increase the tailpipe emissions of milk delivery there are economy of scale savings to operating larger capacity processors; evaluating the tradeoff would require an LCA on processors over a range of sizes.

Increasing the capacity of each farm, thereby decreasing the number of farms, also reduces competition for the closest farms but is offset by the need for more frequent individual trips. If 25% of the farms are chosen at random to be consolidated, reducing the number from 7664 to 5748, with a concurrent increase in milk production of each by 33.3%, each processor would then be served by 43 farms instead of 58. For this case a total of 31,100 km is

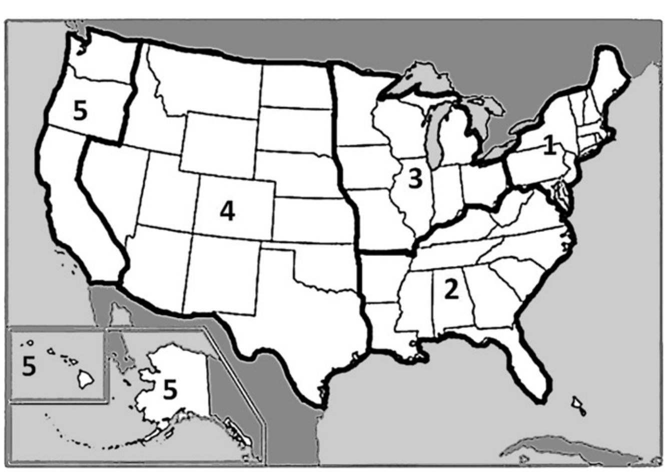

Fig. 7. The five dairy regions used in Table 1.

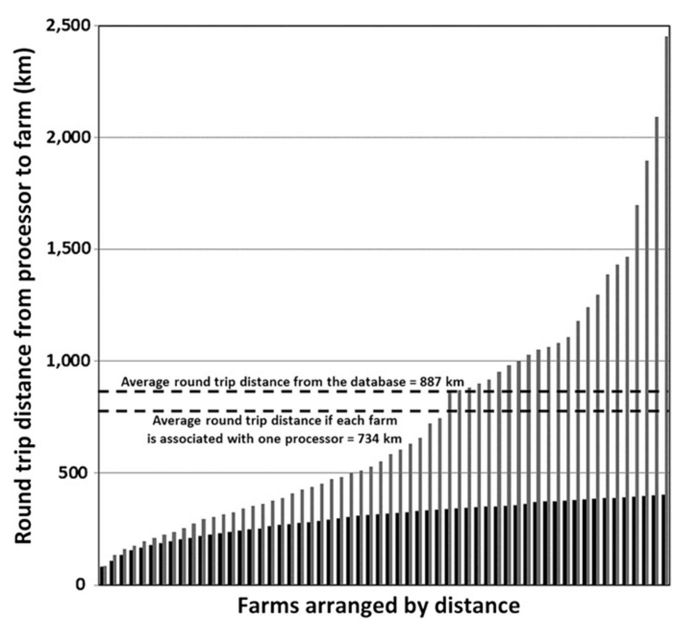

Fig. 8. Average round-trip distances between processors and their closest 58 farms. The black bars are distances for the closest (58) farms regardless of whether or not they are associated with another processor; the gray bars are distances for the closest (58) farms if associated with only one processor.

required to visit each farm individually once but, because the farms are each producing more, they have to be visited 1.333 times more often to deliver the same amount of milk to the plants, so the actual required total round-trip distance is 41,300 km. This is almost equal to the total distance without the farms being consolidated, indicating that the two effects offset each other closely.

4. Conclusions

The CO_2e emissions per mass of delivered milk is quite scattered on a by-state basis in the USA due to the wide range in the ratio of dairy cows to milk drinkers across the geographical area. The fact that the two databases give overall average values fairly close together, 0.052 and 0.045 kg CO_2e per kg milk delivered, suggest that the 18.6% of the market this study captured is at least somewhat representative of the overall fluid milk distribution system. This agreement between databases is despite the fact that the data comes from different types of delivery circuits (Database 1 involves visiting multiple farms per route, and Database 2 is always out and back to one farm) and despite the extensive analysis performed on Database 1 to extract highway driving distances from latitude and longitudes. The overall average from both databases gives 0.050 kg CO_2e per kg milk delivered and 0.071 kg CO_2e per kg milk consumed. This study was part of a cradle-to-grave life cycle assessment of greenhouse gas emissions from milk production (Thoma et al., 2012) that concluded that the overall emissions were 2.05 kg CO_2e per kg milk consumed. Farm-to-processor transport amounts to 3.5% of this total.

There are some strategies that could be employed to decrease the tailpipe greenhouse gas emissions from the trucks but most of the obvious ones are already being utilized to minimize trucking costs arising from fuel and employee time. Long-haul heavy trucks are not likely to become much more efficient in the foreseeable future. For moving heavy cargo long distances on smooth pavement at constant speed, it is hard to improve upon a high-compression diesel engine operating over high-pressure tires. Moving to larger trucks, such as 34,000 L class, or to double trailers could cut the total emissions almost proportionally but would cause increased road wear. There are some opportunities for delivering other sorts of liquid cargo on the empty legs of long trips, a practice known as back-hauling. For instance it might be possible to carry commodities such as orange juice back from Florida, a state that imports most of its milk, but the acidity of citrus juices would require a thorough cleaning of the tank and its associated plumbing on both ends of the trip so is very rarely done.

Increasing the capacity of individual processors increases transportation emissions since the average farm-to-processor distance increases but may be offset by economies of scale at the plants. Farm consolidation has less effect since the routes become shorter but more trips are required. Optimization for specific delivery scenarios requires knowing the production at each farm so that multiple stops can be scheduled for one truck. Some overall reduction in total delivery distance could be realized by realigning farm-to-processor relationships, especially in regions where farms are equally distant from multiple processors.

Acknowledgments

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