MODELING THE RECYCLING INFRASTRUCTURE, FLOWS, AND ASSOCIATED GREENHOUSE GAS EMISSIONS ACROSS THE STATE OF CONNECTICUT

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Abstract

A detailed and localized understanding of the recycling infrastructure, recycling flows, their associated energy consumption and air pollution emissions from processing and transportation provides valuable information for recycling agencies and industry. Such information can help guide regulation and policy decisions on optimizing recycling streams and improving material recovery, recycling, and monitoring. This study builds on a comprehensive REMADE model developed for California (CA)'s recycling infrastructure that includes the mass flows of the major material streams (metals, plastics, fibers, electronic scrap), geolocated by their origin and destination, together with their associated energy use and greenhouse gas emissions, to test the transferability of the CA model and study structure to other U.S. states, namely to Connecticut (CT). Recycling flow data tracked by the CT Department of Energy & Environmental Protection are analyzed to map the quantities of recyclables and waste that are moving across facilities. The emissions associated with the collection and the movements of these material streams will be calculated using the On-Road EMFAC emissions model by standardizing it for CT. This model will be an online tool that will illustrate the different recycling flows across facilities and collection points. The CT submodel will be optimized for transferability to other states to allow a broader application of the developed recycling model in the future.

Introduction and Motivation

An efficient recycling infrastructure is the cornerstone of sustainable material management, a system that prioritizes source reduction and reuse, recycling/composting, and energy recovery over treatment & disposal, as long reflected by the U.S. EPA waste management hierarchy (U.S. EPA, 2025). An efficient recycling infrastructure is also crucial for achieving the National Recycling Goal of a 50 percent recycling rate by 2030 (U.S. EPA, 2021). Tracking progress against this goal requires detailed state-level data on total waste generation and recovery of a host of recyclables (e.g., steel, paper, plastics, glass) from municipal solid waste (MSW), construction & demolition wastes, end-of-life vehicles, and other sources, with data availability and quality varying greatly among the 50 U.S. states.

In parallel, many states face increasing pressure to improve recycling rates and reduce waste, particularly in light of growing concerns about environmental sustainability. In response to this, these states are developing reporting systems to obtain more detailed information about waste and recycling flows. This paper reports on the development of the REMADE-UCI flow analysis model, a unique systems analysis tool that will enable the REMADE Institute, recycling agencies such as CalRecycle, and industry to analyze and project the generation, flow, recycling, reuse, and disposal of scrap metal, e-waste, selected plastics, and fibers from packaging, and their associated net energy consumption and net greenhouse gas (GHG) emissions, under different scenarios. The tool was developed initially using California as a case study and recently applied to Connecticut to test the framework's transferability. For California, its Recycling and Disposal Reporting System (RDRS) served as the primary data source for material-specific flows. The specific tasks included:

- developing a model of the disaggregated generation, flows, and disposal of scrap metal, e-waste, plastics, and packaging in California (from households and firms, as generators to locations where the materials are either recycled, landfilled, incinerated, or exported);
- creating scenarios for years 2020-2050 to analyze changes in the generation, flow, recycling, reuse, and disposal of these materials. Scenarios are informed by economic and population growth projections, and

consider household recycling behavior, the impact of existing and pending California recycling legislation, and broader trends such as the electrification of transportation, and the rise of online shopping.

- developing the capability to conduct material flow analyses (MFAs) that provide estimates of energy consumption and GHG emissions that result from changes in the generation, flow, recycling, reuse, and disposal of recyclable materials.

This model can be employed as a descriptive model that represents the measured flows by a state's reporting system or for policy analysis to optimize system performance over parameters representing policy alternatives.

Like California, Connecticut (CT) has access to detailed waste and recycling data that are the basis for successfully applying the REMADE-UCI model. Waste data are publicly available through the CT Department of Energy and Environmental Protection, but access to individual material streams is cumbersome and not intuitive. The UCI-REMADE tool allows developing a holistic waste infrastructure model that ensures that all information is in one place and comprehensive. Furthermore, by categorizing the waste types and their respective flows it shows the pathways and routes that waste takes across the state and beyond its boundaries.

Review of Related Work

In MSW management systems, the collection and transportation of waste often accounts for a substantial fraction of both operating costs and environmental impacts (Neto et al., 2024; Yang et al., 2024). This means that optimizing the waste travel path logistics can be as crucial as end-of-life management for a sustainable waste management system. Currently, there is a body of research that focuses on route design (Das & Bhattacharyya, 2015; Son & Louati, 2016; Vecchi et al., 2016), fleet allocation, container placement, and scheduling of vehicular routes of waste travel (Hess et al., 2024; Li et al., 2025) while minimizing distance and cost. However, many of these models neglect environmental externalities and greenhouse gas emissions from the collection vehicles. Life cycle assessments (LCA) are abundant in waste systems research as LCA allows the quantification of environmental burdens across the entire waste management chain (Zhang et al., 2021). While some LCA studies such as Aryan et al. (2023) include transport emissions, we are not aware of any study that combines travel and vehicle logistics, especially within the United States of America, although similar studies have been conducted in China (Liao et al., 2024).

Waste management strategies remain an integral part of circular economy conversations, and optimal recycling strategies are required to reach the cradle-to-cradle ideal (Khan et al., 2025). A report from the National Academies Press (2025) notes that a large fraction of MSW is not recycled or composted under current U.S. practices due to multiple cross-disciplinary challenges and the need for quick and cheap solutions with high magnitudes of waste. While it would be easier to tackle waste diversion on a more granular, state specific note, most models and data available to the public paint a broader or national picture; statewide solid waste generation data is not easily found or publicly aggregated (Rogoff & Ross, 2017). Furthermore, the waste systems in the US remain highly fragmented across states with substantial variations in infrastructures, recycling policies, and outcomes. It is important to look at state-specific waste scenarios and their associated emissions.

Technology Approach

To meet the objectives described above, our modeling framework includes the following characteristics:

- It represents the main components of a state's waste and recycling industry;
- It tracks the flows of specific materials in the state, grouped into categories such as recycled metals, fibers, plastics, and e-waste;
- It provides a partial material flow analysis of energy and GHG emissions related to recycling and reuse of these materials;
- It is embedded in a transportation model, thus providing the backbone for a robust logistics model; and
- It allows for policy analysis.

The overall methodology involves the following steps:

1. Identify independent layers of material flows
2. For each layer:
    a. Find the unique flow origin and destination endpoints
    b. Geocode each endpoint, including the selection of representative points (or centroid) for endpoints in aggregated regions (cities, counties, etc.)
    c. Determine the transportation mode(s) and route for each unique origin/destination pair, to calculate the number of trips loaded onto each segment of the transportation network

  d. Compute the energy use, and emissions associated with the loaded flows by material type.
3. Join flows from all layers for a complete representation of impacts in the modeled regions

Model Implementation

The model pipeline was implemented in python leveraging a range of common libraries including the geopandas library for geographic data analysis to integrate and manipulate the disparate data sources into a common framework. We also used several libraries integrating external tools for modeling the flows of individual layers as well as their resulting impacts, which are described below. The model system and public data will be released as an open-source tool at the completion of the project. In California, the model layers include:

- the Recycling and Disposal Reporting System (RDRS**)** that records quarterly reports of materials sold and transferred by specific mandated reporting entities that include: recycling facilities, composting facilities, disposal facilities (including landfills), transformation facilities, engineered municipal solid waste conversion facilities, transfer/processor facilities, contract haulers, food waste self-haulers, brokers, and transporters;
- Metal flows from appliance recycling as reported by the 2019 Residential Appliance Saturation Study (RASS);
- eWaste recycling as reported by California's Department of Toxic Substances Control (DTSC); and
- Various material flows from end-of-life vehicle dismantling using vehicle retirement data from the DMV.

In Connecticut, CT DEEP flow data closely resembles RDRS data, capturing flows between specific facilities for various classes of materials.

Endpoint geocoding for both states involves a combination of data sources and methods. In California, RDRS contains some information about the locations of endpoints for reported flows. Some endpoints-particularly those representing aggregated areas for collection or end use-are not geocoded and require other geographic datasets including census data and world geographic boundary data. In these cases, a representative point for the area is used as the transportation endpoint. The CT DEEP data includes addresses for most endpoints. They were geocoded using online sources as well as the Nominatim geocoder (Nominatim, 2024). As with the California RDRS data, some endpoints represent aggregated areas that were geocoded as described previously.

We next consider the modes used for these point-to-point commodity flows. The main modes for transporting commodities—including waste—is trucking (for California and Connecticut) and rail within California. Neither state has a significant network of navigable waterways used for waste transport. A significant fraction of recyclables is exported outside of the United States, although there has been increasing domestic demand for recycled higher-grade alloys in recent years. In California, most recyclable materials or scrap exports go through maritime ports. However, some exports of recyclable materials also go through Mexico's land border crossings. While anecdotal evidence suggests that some recyclable materials are exported via rail, the quantities are too small to be captured in available datasets so we assumed that all waste commodity movements with an origin in California are transported by road. When destinations are not directly reachable via the road network, we assume a maritime leg, but as this does not apply to Connecticut, we omit these details for brevity. Similarly, the Connecticut data only contains a limited subset of flows to international endpoints, nearly all of which are in Canada. There are a few endpoints outside of North America, but most export flows are likely handled by intermediate processors whose outflows are not captured by CT-DEEP.

Our focus is therefore on the on-road flows. These first must be converted to equivalent vehicle trips using payload factors (in tons/truck). This requires identifying the type of vehicles used, which is a function of the material transported, vehicle configuration, and additional complex factors (e.g., see Harris et al., 2024). The Freight Analysis Framework (FAF) produced by the Federal Highway Administration (FHWA) uses payload factors for waste commodity movements[1] ranging from 20.50 to 21.19 tons/truck (FHWA, 2020; Hwang et al., 2021). However, this aggregate value does not distinguish between waste commodity subtypes. Given the variability of waste commodities (from paper and plastics to steel and construction debris) and our desire to represent distinct material streams for analysis, we developed model-specific factors.

First, we mapped each on-road material stream movement to a vehicle class in California's On-Road Emissions Factors (EMFAC) model (CARB, 2021), with most trips modeled using Class 8 Tractors (T7 - Tractor). This category includes multi-unit (tractor/trailer) day cab trucks making in-state single day trips (as distinct from a

[1] Standard Classification of Transported Goods 41: Waste and Scrap.

sleeper configuration). We assume these trucks capture all non-port, high weight and/or high volume material movements.

After selecting vehicle types for each model layer, trip type, and material grouping, we considered payload factors. Converting T7 (Class 8) trips from tonnage of flow to vehicle trips requires a material specific payload factor. To develop them, we considered the density of each material to understand whether the weight capacity ($W_{t,\mathrm{cap}}$) or volume capacity ($V_{t,\mathrm{cap}}$) will be reached first for material trip type t. We also assumed that the density ρ of the material moved is known, so the capacity for a given trip type is the tonnage that is the lesser of the vehicle's weight limit and its volume limit. Assuming that the payload factor approaches capacity, the payload factor is:

$$f_{t,max} = \min(W_{t,cap}\,,\ \rho_t V_{t,cap})$$

The weight limits are a function of truck GVWR and must be estimated from industry standards. For instance, a 50,000 lb. payload is a reasonable estimate for an MSW tipper truck.[2] However, the volume limit depends on the trailer used. While the tipper may achieve a capacity exceeding 100 yd^3 this may overstate capacity for longer haul trucks that require heavier, or different trailer configurations. These are applied to convert on-road flows to volume of vehicle trips ($v_{i,j,t}$) from origin i to destination j for material trip type t as follows:

$$v_{i,j,t} = \sum_{c\forall \in C} \frac{x_{i,j,t}\ y_{i,j,t,c}}{f_{t,c}}$$

where: $v_{i,j,t}$ is the volume of trips from origin i to destination j for material trip type t;

$x_{i,j,t}$ is the flow from origin i to destination j for material trip type t. This is provided by the layer or dataset;

$f_{t,c}$ is the payload factor for material trip type t for container type c, from Table 4; and

$y_{i,j,t,c}$ is the fraction of flow from origin i to destination j for material trip type t transported using container type c. This is an unknown value that must be estimated.

If we make a simplifying assumption that all on-road movements will use either 20ft or 40ft containers, $y_{i,j,t,c}$ can be estimated by adjusting them so that the flow-weighted averages of all material stream payload factors equal the blended Freight Analysis Framework payload factors. In this analysis, most materials are constrained by weight limits, which gives a payload factor of 20.6 tons/trip. One important exception is plastic, which is constrained by volume limits, resulting in a payload factor of 13.3 tons/trip.

Route determination and Flow Assignment

After completing an enumeration of geocoded point-to-point origin-destination (OD) flows by material type that include point-to-point on-road trips (which may be split across multiple vehicle classes), we assigned all layer trips between a given OD pair to the same shortest path (i.e., an all-or-nothing assignment) because the truck flows of the waste recycling system are likely to be negligible compared to total network flows.

To route domestic on-road trips, we found the shortest/best path between each OD pair using the Open Source Routing Machine (Project OSRM, 2024) with the California and Connecticut OSM extracts (OpenStreetMap, 2024)[3]. We represented routes as a set of joined links with geographically correct geometries to capture accurate distances. Operational parameters attached to each link include the average speed needed for emissions calculations.

For each path, we further segmented the route sections by splitting them between regions for emissions modeling. In California, we used the EMFAC model's County/Air Basin/Air District (CoAbDis) boundaries to later facilitate energy and emissions calculations. For the Connecticut model, we used state boundaries for emissions modeling regions. To extend the California model to Connecticut, we mapped each state to a representative CoAbDis region to obtain emissions rates using a similarity score computed on the basis of latitude, climate zone type, elevation, and average temperature.[4] Once routes have been determined for each OD pair we computed on-road VMT by OD-material pair route subsegment, taking into account the number of trips traversing the subsegment and its length.

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[2] Sabol (2001) cites an anecdote from hauler using MSW to tipper trucks: "I spec our tipper trailers to haul a 115 cubic yard capacity. These trailers weigh less than 13,000 pounds each, which nets 50,000 pounds of payload per trip."

[3] The use of state extracts rather than a full US extract was driven by computing resource limitations. For the OD pairs across state boundaries, an online OSRM service was used to obtain routes.

[4] Work is ongoing to determine emissions rates for non-California locations using the EPA MOVES model but was not complete at the time of press.

Energy and Emissions Estimation

We used CARB's EMFAC model to estimate emissions resulting from on-road flows. EMFAC provides emissions rates by vehicle class, fuel type, CoAbDis region, and speed bin. For a given vehicle class, we assumed that the share of fuel types used is proportional to the EMFAC VMT by fuel type, so we calculated emissions rates for each class as the VMT-weighted mean of rates associated with each fuel type. We then multiplied emissions rates by VMT to calculate emissions for each OD-material on that segment, before aggregating the results for analysis by county, ODs and material type to obtain tons sent, trips, VMT, and particulate (PM_{25}), criteria (NO_X) and total GHG emissions[5]. Table 1 compares the resulting on-road flows with their associated emissions, by material type and by the State from which they originated. We've also highlighted the classes with longest average trips and highest emissions per tonne of material sent.

Table 1. Comparison of Connecticut and California on-road material flows with emissions, year 2021.

Material	State	Material Sent (tonnes)	Percent of state total	Trips	VMT	PM25 (kg)	NOx (tonnes)	GHG (tonnes)	VMT per Tonne sent	VMT per Trip	g PM25 per Tonne sent	g NOx per Tonne sent	g GHG per Tonne sent
Ash	CT	1,536,092	16.74%	76,805	3,806,790	194.0	8.6	5,938	2.48	49.565	0.126	5.59	3,865.7
CD	CA	9,316,128	16.59%	465,806	21,093,682	1,130.5	51.1	33,911	2.26	45.284	0.121	5.48	3,640.0
CD	CT	547,485	5.97%	27,374	1,067,707	55.3	2.5	1,698	1.95	39.004	0.101	4.58	3,102.0
Cardboard	CA	2,346,444	4.18%	117,322	64,327,197	3,430.6	132.4	97,808	27.41	548.295	1.462	56.42	41,683.7
Ferrous	CA	699,584	1.25%	34,979	10,075,489	529.1	21.0	15,317	14.40	288.042	0.756	30.04	21,895.0
Ferrous	CT	10,615	0.12%	531	47,339	2.4	0.1	76	4.46	89.193	0.223	10.02	7,133.8
Glass	CA	1,224,901	2.18%	61,245	5,716,458	298.1	12.2	8,819	4.67	93.338	0.243	9.99	7,200.0
Glass	CT	44,775	0.49%	2,239	83,541	4.2	0.2	130	1.87	37.316	0.095	4.17	2,909.2
HDPE	CA	111,700	0.20%	5,585	2,823,097	150.8	5.8	4,300	25.27	505.480	1.350	52.16	38,494.7
MSW	CA	25,562,337	45.52%	1,278,117	40,927,063	2,127.4	96.6	65,454	1.60	32.021	0.083	3.78	2,560.6
MSW	CT	4,667,723	50.88%	233,386	48,864,388	2,470.3	100.2	73,862	10.47	209.371	0.529	21.46	15,824.0
Mixed Metal	CA	342,357	0.61%	17,118	3,259,247	173.6	7.1	5,023	9.52	190.401	0.507	20.64	14,673.2
Mixed Metal	CT	156,013	1.70%	7,801	489,002	24.3	1.1	757	3.13	62.687	0.156	6.77	4,854.0
Mixed Plastic	CA	171,356	0.31%	8,568	4,384,826	232.8	9.0	6,671	25.59	511.779	1.359	52.62	38,929.0
Mixed Plastic	CT	11,631	0.13%	582	112,350	5.6	0.2	172	9.66	193.198	0.485	20.52	14,791.3
NonFerrous	CA	293,763	0.52%	14,688	11,982,871	642.3	24.5	18,197	40.79	815.820	2.186	83.46	61,946.1
NonFerrous	CT	9,671	0.11%	484	93,634	4.6	0.2	143	9.68	193.629	0.473	19.93	14,762.5
Organics	CA	11,821,535	21.05%	591,077	56,437,641	2,957.1	125.7	88,199	4.77	95.483	0.250	10.63	7,460.9
Organics	CT	632,728	6.90%	31,636	1,828,298	94.0	4.2	2,886	2.89	57.791	0.149	6.63	4,561.3
Other	CA	1,163,483	2.07%	58,174	10,041,246	533.3	21.1	15,366	8.63	172.607	0.458	18.10	13,206.5
Other	CT	456,547	4.98%	22,827	1,795,932	91.5	3.9	2,786	3.93	78.675	0.200	8.63	6,102.2
PET	CA	305,189	0.54%	15,259	4,117,900	217.1	8.4	6,258	13.49	269.859	0.711	27.68	20,505.8
PET	CT	6,066	0.07%	303	103,448	5.1	0.2	157	17.05	341.074	0.848	35.04	25,820.3
Paper	CA	1,355,388	2.41%	67,769	48,668,964	2,579.7	99.6	73,849	35.91	718.156	1.903	73.48	54,485.2
Paper	CT	452,023	4.93%	22,601	2,304,101	118.1	5.1	3,581	5.10	101.946	0.261	11.22	7,921.7
SingleStream	CA	1,446,183	2.58%	72,309	3,700,511	190.9	8.3	5,798	2.56	51.176	0.132	5.71	4,009.0
SingleStream	CT	635,155	6.92%	31,758	797,706	42.4	2.0	1,304	1.26	25.119	0.067	3.18	2,053.1
eWaste	CT	8,299	0.09%	415	65,820	3.3	0.1	100	7.93	158.615	0.397	16.45	12,060.5
TOTAL	**CA**	**56,160,346**		**2,808,017**	**287,556,192**	**15,193**	**623**	**444,971**	**5.12**	**102.405**	**0.271**	**11.09**	**7,923.2**
TOTAL	**CT**	**9,174,822**		**458,741**	**61,460,057**	**3,115**	**129**	**93,590**	**6.70**	**133.975**	**0.340**	**14.02**	**10,200.7**

Note: Materials are boxed together for easier comparison between CA and CT. Some materials are only reported for one of the states. Red shading in the VMT and emissions columns highlights the material flows with the highest VMT and emissions per tonne.

The results show nonferrous metals (61.9 kg GHG/tonne sent) have the highest emissions per tonne of all materials considered for both California and Connecticut. This is due to large flows of these materials being sent across the country. Paper (54.5 kg GHG/tonne sent) and Cardboard (41.7 kg GHG/tonne sent) from California as well as plastics also show high emissions rates for California[6]. For Connecticut, the highest emitting material is PET (25.8 kg GHG/tonne sent), followed by MSW (15.8 kg GHG/tonne sent) and Mixed Plastic (14.8 kg GHG/tonne sent).

Discussion

Connecticut has had a Solid Waste Management Plan in place since 1991 (amended in 2006; CT DEP, 2006) that aims at significantly reducing the amount of solid waste by increasing source reduction, reuse, recycling, and composting, among others (CT DEP, 2006). Within the United States, CT is unique in that the landfilling of recyclable materials has been banned since 1991, a result of limited in-state landfill capacity. Non-recycled MSW is

[5] GHG emissions are computed as $GHG = CO_2 + 28\,CH_4 + 265\,N_{2O}$ per IPCC (2014)

[6] Some of the longer flows for paper and plastics from California may be a reporting artifact stemming from misreporting of exporters in the data. We are continuing to refine our endpoint definitions to capture these effects.

burned at regional incinerators ("resource recovery facilities," RRFs), leading to a substantial volume reduction of waste requiring landfilling and making Connecticut the state most reliant on waste-to-energy facilities in the country (ibid). Most of Connecticut's RRF ashes are landfilled in Putnam, CT (CT DEEP, 2023a), the state's only MSW ash landfill, fed since 1999 by regional incinerators from Hartford (until 2023) and Bridgeport, among others.

California moved in the opposite direction due to air quality concerns, with only a handful of incinerators operational by 2000 and the last two remaining incinerators shut down by the end of 2024. Figure 1 compares the proportion of materials in the waste stream by tonnage between California and Connecticut and illustrates this difference (also see the fourth column in Table 1). Nearly 17% of Connecticut's waste tonnage was ash whereas California (in 2021) effectively had none. California reported higher proportions of both construction debris (CD, 17% vs 6%) and organics (21% vs 7%). Most other materials had similar proportions, with MSW in both states accounting for 45-50% of tonnage and other materials showing similar proportions.

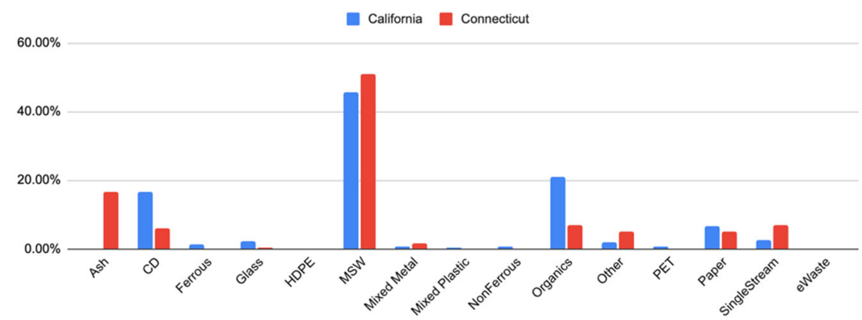

Figure 1. Proportion of Materials in Waste Stream by Tonnage

In 2023 CT replaced its Solid Waste Management Plan with the Comprehensive Materials Management Strategy Amendment (CT DEEP, 2023b) to address the reduced waste disposal capacity in the state, a result of one of its largest waste incinerators in Hartford closing in 2022 (the Material Innovation and Recycling Authority's RRF; Rosengren 2022). That closure was responsible for a sharp increase in the amount of MSW exported for out-of-state disposal, increasing from 17% in 2021 to more than 40% in 2023 (Giannetti, 2025).

The following figures demonstrate the power of the REMADE-UCI flow analysis model in illustrating the travel of waste and recycling material flows within and across state borders. Figure 2 shows the material flows that begin and end within Connecticut's borders in 2021. There are 13 different materials shown: ash, construction & demolition (CD), glass, MSW, metals (mixed, non-ferrous; note that no ferrous flows are shown here as most of Connecticut's ferrous scrap is exported to Massachusetts), plastics (PET, mixed plastics), organics, other, paper & cardboard ("paper"), single stream, and e-waste. The largest flows show MSW incinerator ash originating in Bridgeport and heading to the ash landfill in Putnam.

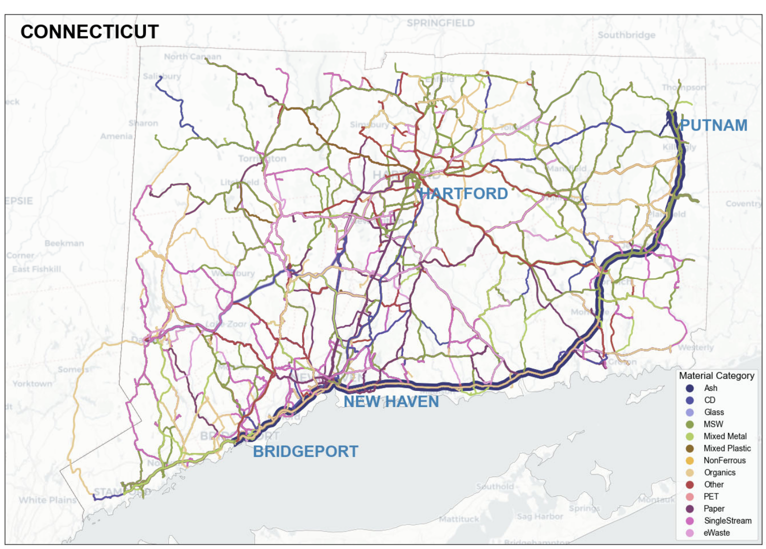

Figure 2. Waste and recycling flows by material with origins and destinations within Connecticut, year 2021.

The total of all waste and recycling flows originating in Connecticut are shown with trip lengths of less than 1,000 miles (basically excluding marine shipping) are shown in Figure 2. Most of this waste travels through Pennsylvania to Ohio, but substantial flows also exist to Georgia, Virgina, Michigan, and various Canadian border crossings. From the underlying DEEP dataset we infer that shipments to Ohio and Pennsylvania are predominantly for final disposal in landfills. Destinations in other states provide a mixed picture of recyclables either further processed or sent to brokers for further shipment (e.g., from New Jersey to China).

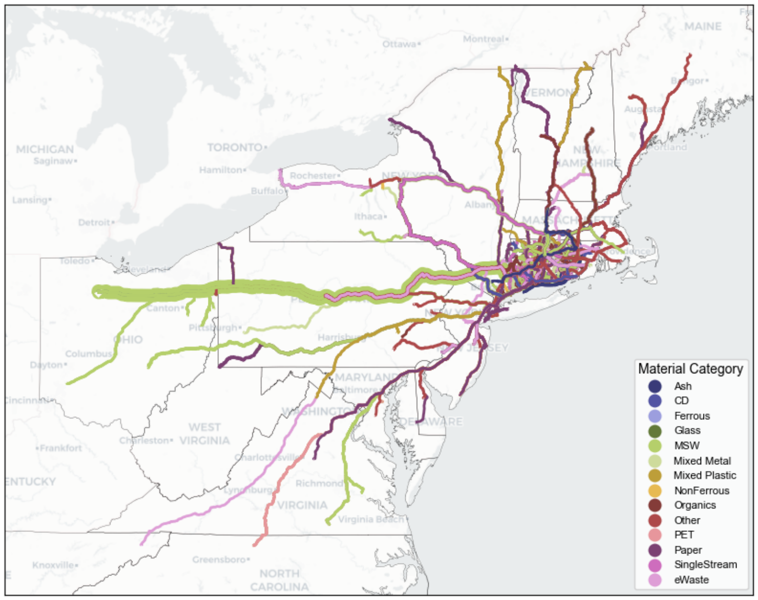

Figure 3. All waste and recycling flows originating in Connecticut of more than 1,000 tons, year 2021.

The tool also allows making comparisons of trip characteristics across states. Figure 3 provides an example by showing the length of trips across all materials for both California (top) and Connecticut (bottom). A striking difference immediately stands out: a relatively homogeneous trip length distribution in California (most ranging from 0 to 100 miles) contrasts with a rather heterogeneous trip length distribution in Connecticut. In California, most trips have a length of around 50 miles compared to less than 10 miles in Connecticut. While most trip lengths in Connecticut are less than 50 miles, many trips also have lengths of 100 to even 750 miles. This can be explained by Connecticut being a relatively small state that depends on the specialized recycling infrastructure in other states (e.g., plastics recycling), but also on landfilling some of its non-recycled MSW (in Ohio and Pennsylvania, among others).

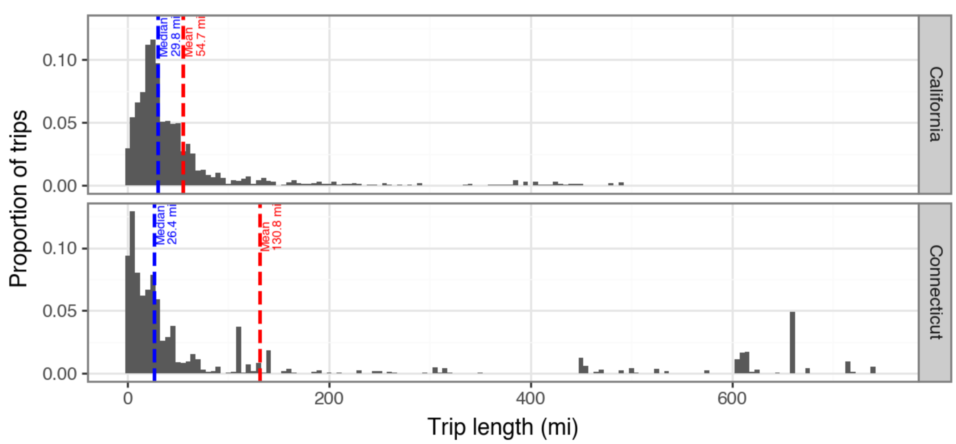

Figure 4. Trip length distributions for waste flows by origin state, year 2021.

Conclusions & Recommendations

This study successfully adapted the comprehensive REMADE-UCI flow analysis model, which was originally developed for the State of California, to the State of Connecticut. It shows the model's robust transferability and its utility as a localized, data-driven instrument for analyzing regional recycling infrastructure, material flows, and associated environmental impacts. By transferring California's On-Road EMFAC emissions to the Connecticut context and integrating waste flows data from the Connecticut Department of Energy and Environmental Protection (CT DEEP), we have illustrated that the REMADE-UCI model can serve as a platform to map the movement of major material streams, including municipal solid waste (MSW), ash, construction and demolition (C&D) waste, glass, metals, plastics, and paper, both within state borders and across state lines.

The detailed analysis of Connecticut's waste flows highlights salient characteristics and challenges inherent in the state's materials management system. First, Connecticut's historical prohibition on landfilling recyclables and its substantial reliance on Waste-to-Energy (WTE) facilities are defining structural elements that differ significantly from waste management in California. The visual flow analysis, particularly in Figure 2, clearly delineates the dominant streams of MSW incinerator ash primarily destined for the Putnam ash landfill, originating from key regional hubs such as Bridgeport and New Haven. Second, even before the cessation of operations at the Hartford WTE facility in 2022 flows to landfills in Ohio and Pennsylvania were already substantial.

The REMADE-UCI flow analysis model and its specific application to Connecticut provides essential information for policymakers and industry stakeholders. The geolocated and material-specific flow data are foundational for designing optimized collection logistics, pinpointing structural bottlenecks within the recycling value chain, and serve as the basis to accurately quantify the environmental burdens imposed by current practices.

Our analysis suggests several recommendations pertinent to Connecticut and for other applications of our approach. The state of Connecticut should consider the following: (1) Augmenting in-state processing capacity, particularly for materials currently necessitating long-distance shipment, such as several plastics, to mitigate transportation-related emissions and operational costs; (2) Developing targeted policy scenarios to rigorously evaluate the GHG and vehicle miles traveled (VMT) impacts of various waste management alternatives, including enhanced source reduction, expanded composting programs, and localized WTE alternatives.

One limitation of this work is our reliance on EMFAC to estimate emission factors for Connecticut when the regulatory standard for emissions calculations outside of California is to use the EPA's MOVES model. Though the models are related and share some methodologies, EMFAC is designed to account for California-specific factors related to fleet composition, meteorological data, and fuel specifications. Thus, even though the resulting emissions factors are similar, prior work has noted variations for some vehicle classes that can impact results (Bai et al, 2008). As such, future applications of this model system should rely instead on emissions calculated from the MOVES model.

Other sources of uncertainty need to be refined. Assumptions related to the payload factor estimation and maximizing loads may underestimate the number of trips necessary to move tonnage. Additional sources of data, such as the national Vehicle Inventory and Use Survey (VIUS)[7] offer a potential avenue for better estimating payload factors. Similarly, assumptions regarding shortest-path routing certainly represent a lower-bound on VMT whereas actual routes are likely longer due to factors not directly represented such as multi-stop tours, hauler preferences, and other unknown factors. The error introduced by these routing assumptions is likely small, but future work should attempt to quantify it. Additional effort is needed to align model results with export data to more accurately capture outflows. We are working to achieve this alignment using export datasets that include the national quinquennial Commodity Flow Survey, the Surface Transportation Board Rail Waybill Sample, the previously mentioned VIUS, as well as private datasets like the Port Import/Export Reporting Service (PIERS) leveraging bills of lading.

Future work should also concentrate on further generalizing the data processing for our model to facilitate rapid deployment to other U.S. states. We note, however, that most U.S. states do not collect systematically data on their recycling infrastructure and material flows between facilities. Another useful development would be to enhance our model's capacity to analyze a wider spectrum of recyclable materials. This application to Connecticut shows our model's potential to deliver localized, data-driven insights needed to facilitate the transition toward a more circular economy.

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[7] https://www.bts.gov/vius

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