SOURCE SEPARATION VS. CENTRALIZED PROCESSING: AN AVOIDED-COST OPTIMIZATION MODEL PROVIDES SOME INTRIGUING ANSWERS

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ABSTRACT

What point in the flow of waste, from generator source to disposal site, presents the best opportunity for diversion of recyclables? Based on an avoided-cost optimization analysis, this paper examines the potential for source separation versus processing mixed waste to recover recyclable materials and compost. In the Puget Sound region of Washington state when disposal costs are above $50 per ton and recyclable materials have reasonably good markets, the model projects that an urbanized community should pursue both intensive source separation and mixed waste processing. By targeting more materials than traditional bottle, can and newspaper programs, intensive source separation can achieve a 50 percent recycling rate. Then front-end separation and mixed waste composting can be used to divert additional materials from the mixed waste that escapes the source separation net and lands in the garbage can. The result is disposal of only about 15 percent of generated waste. Sensitivity analysis suggests that the range of disposal costs and market prices in which source separation and mixed waste processing/composting are competitive with each other is too narrow to warrant consideration in a community's long-range waste management plan.

This paper describes some surprising results from using an avoided-cost optimization model[1] to decide whether source separation methods are more economical than centralized processing methods for recovering household or commercial recyclables and compostables.

The model was developed for the Washington State Department of Ecology's *Best Management Practices Analysis for Solid Waste* to answer the Washington State Legislature's question: What point in the flow of waste, from generator source to disposal site, presents the best opportunity for diversion of recyclables? In an urban area of 125,000 single-family households that is close to major recycled materials markets, that analysis showed that curbside collection of source separated materials and centralized processing of remaining unseparated wastes were both economical and complementary diversion methods, given disposal costing about $50 per ton and 1988 market prices for recycled materials, including container, film and packaging plastics.

The options for waste stream management that were analyzed by the optimization model included buy-back centers, curbside recyclables collection, curbside yard waste collection, curbside food waste collection, drop-off centers, hand-sorting of recyclables from mixed waste, highly mechanized sorting of recyclables from mixed waste followed by mixed waste composting, and disposal. For each management option, participation and separation efficiency parameters for each of 23 waste stream materials define recovery potential if a particular material is chosen for diversion using a particular waste management option. Figure 1 illustrates how these waste management methods fit into an integrated waste management plan.

Tables 1 and 2 list model input parameter data including: participation and separation efficiencies; waste composition; market prices for recovered materials; and collection truck loading capacities, loaded material densities, and

[1]*The model, called CurbConserve, is based on linear programming with a manual subroutine that takes into account nonlinear collection costs. Data on density (compacted or not compacted), market price and recoverability of waste stream components for the recycling and composting methods, including collection truck stopping, loading and tipping efficiencies and costs, are based on real-world information developed in 1988/89 by the consulting team that conducted Washington state's Best Management Practices Analysis for Solid Waste. (A more detailed discussion of the CurbConserve model and the results reported in this paper are presented in a discussion paper available from Sound Resource Management Group, 206/932-3404.)*

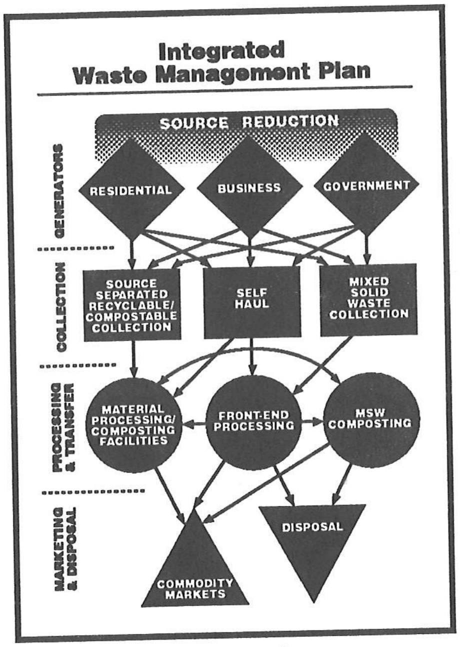


Figure 1

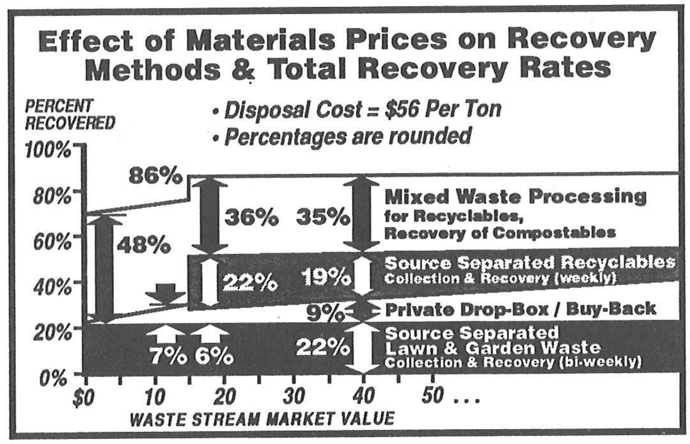


Figure 4

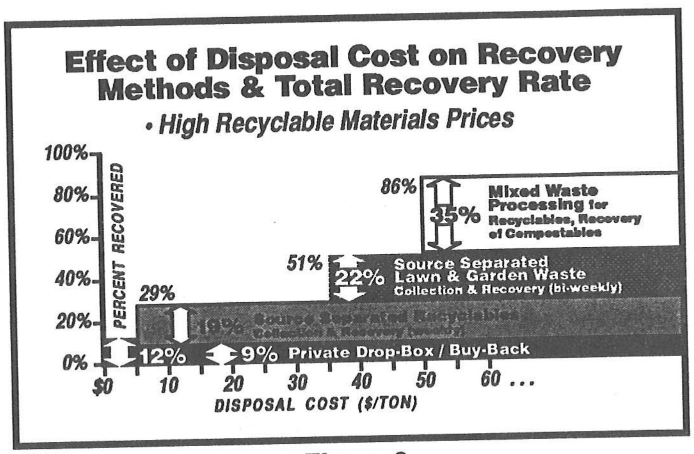
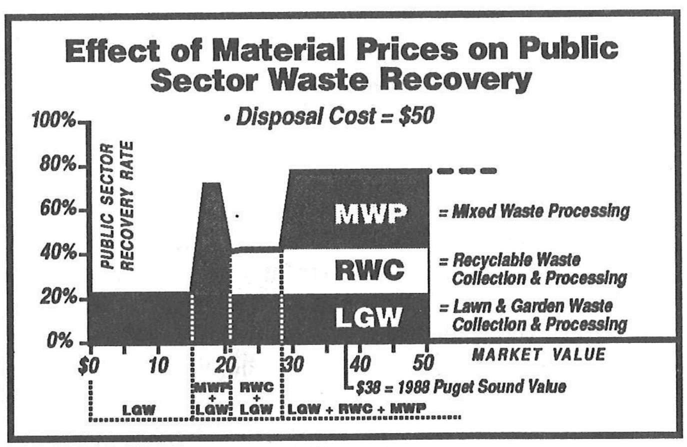


Figure 2



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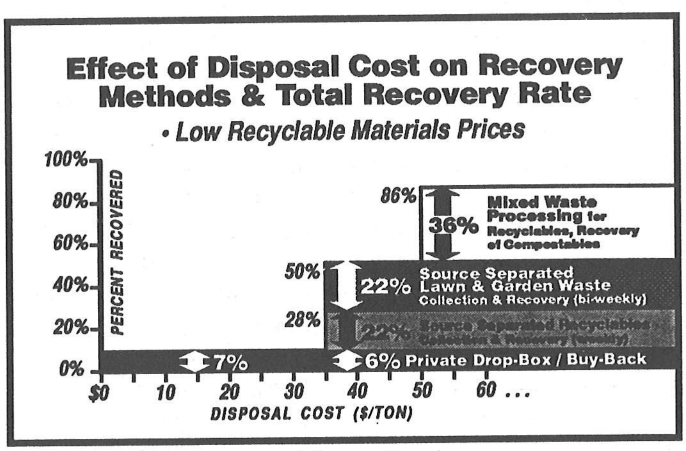

Figure 3

Table 1

Waste Stream Composition and Density Data, Separation Parameters, and Material Price Parameters (1)

Waste Component	1987 Residential Drop-Off & Buy-Back Recycling Rate	RECYCLABLES SEPARATION EFFICIENCY: Home Sorting for Curbside Collection	RECYCLABLES SEPARATION EFFICIENCY: Mixed Waste Process (MWP) Sorting	RECYCLABLES SEPARATION EFFICIENCY: Hand Pick Only Sorting	Compost Process Capture Rate During MWP Sorting	1987 Puget Sound Residential Single-Family Waste Composition (2)	COLLECTION TRUCK Waste Density (lbs./cu.yd.): Recycle Truck	COLLECTION TRUCK Waste Density (lbs./cu.yd.): Refuse Truck	Source Separated Materials Market Price per Ton	Materials Sorted from Mixed Waste Market Price per Ton	MWP Composted Materials Market Price per Ton
Newsprint	64%	85%	15%	15%	70%	11.6%	500	900	$45	$23	$0
Corrugated Cardboard	29%	85%	50%	50%	35%	5.2%	150	600	$65	$33	$0
High Grade Paper	0%	85%	15%	0%	70%	0.3%	500	900	$100	$50	$0
Mixed Waste Paper	0%	85%	15%	0%	70%	10.4%	150	700	$25	$13	$0
Refillable Glass Containers	65%	50%	60%	60%	0%	0.7%	400	1,000	$116	$12	$0
Other Recyclable Glass	15%	50%	60%	60%	0%	5.9%	400	1,000	$40	$12	$0
Aluminum Beverage Containers	26%	85%	60%	60%	0%	0.8%	75	150	$1,000	$750	$0
Tin Food/Beverage Cans	2%	40%	80%	0%	0%	1.9%	150	300	$49	$37	$0
Ferrous Metals	54%	0%	80%	40%	0%	1.5%	650	750	$65	$49	$0
Non Ferrous Metals	29%	0%	40%	40%	0%	0.4%	400	500	$800	$400	$0
White Goods	89%	0%	85%	85%	0%	1.7%	400	400	$20	$10	$0
PET Bottles	0%	50%	25%	25%	0%	0.3%	40	300	$160	$48	$0
HDPE Bottles	0%	50%	25%	25%	0%	0.4%	24	300	$200	$60	$0
Plastic Packaging/Film	0%	35%	0%	0%	15%	4.4%	50	300	$160	$48	$0
Other Plastics	0%	0%	0%	0%	15%	0.9%	50	300	$0	$0	$0
Tires	0%	0%	75%	75%	5%	0.4%	500	500	$0	$0	$0
Other Rubber Products	0%	0%	0%	0%	20%	0.2%	400	600	$0	$0	$0
Food	0%	90%	0%	0%	95%	8.2%	750	1,000	$0	$0	$0
Lawn & Garden Waste	0%	90%	0%	0%	90%	26.9%	415	415	$5	$0	$0
Wood Waste	0%	75%	25%	25%	65%	1.6%	300	600	$5	$0	$0
Construction/Demolition (Excl. Wood)	0%	0%	25%	25%	10%	0.7%	800	1,000	$0	$0	$0
Other Organic Waste	0%	0%	0%	0%	90%	9.2%	600	900	$0	$0	$0
Other Inorganic Waste	0%	0%	0%	0%	30%	6.2%	600	750	$0	$0	$0
Total/Average						**100.0%**			**$38**		

(1) *CurbConserve* Model Version:

- Weekly Recyclables, Food & Refuse Collection
- Biweekly Yard Waste Collection
- 125,000 Single-Family Urban Residences (1–4 Families per Building) in the Puget Sound WGA

(2) Includes 11.7% of self-hauled waste.

Source for sorting efficiencies and waste densities: Washington State Department of Ecology Best Management Practices Analysis for Solid Waste, Volume III, January 1989.

Table 2

Truck Route and Collection Cost Parameters; Processing and Disposal Cost Parameters

A. General Data

Daily Waste Volume (tons per working day)	500	
Housing Density (number per road mile)	125	
Waste per Household (numbers per week)	40	
Participation		
• Refuse	95%	
• Recyclables	75% (Weekly Set-Out Rate = 50%)	
• Self Haul	5%	
• Food Waste	90%	
• Yard Waste	90%	
Container Costs (10-year life)		Amortization @ 4%
• 60-gallon Refuse	$50	$6.16
• 3 @ 11-gallon Recycling	$18	$2.22
• 5-gallon Food Waste	$10	$1.23
• Yard Waste	$0	$0.00
Processing Costs per Input Ton		
• Recyclables	$22	
• Mixed Waste	$40	
• Food Waste	$40	
• Hand Pick	$20	
• Yard Waste	$23	
Disposal Costs per Ton	$50	

B. Truck Data

Speed (mph)	
• Between Stops	10
• To/From Route or Tippng	30
Capacity (cubic yards)	
• Yard Waste	32
• Recycling	20
• Refuse	20
• Food Waste	2
Collection Stop Time (hours)	
• Recycling	0.008
• Refuse	0.006
• Yard Waste	0.006
• Food Waste	0.006
Average Distances (miles)	
• Base to Route	10
• Route to Recycling Center	15
• Route to Processng or Disposal Site	15
• Center or Site to Base	15
Tipping Time (hours)	
• Recyclables	0.500
• Refuse	0.500
• Food Waste	0.167
• Yard Waste	0.333

C. Daily Collection Information

	Recycling	Food Waste	Yard Waste	Refuse
Potential Set-Outs	12,500	25,000	12,500	25,000
Participant Set-Outs	9,375	22,500	11,250	23,750
Collected per Household (lbs.)	21	0	19	20
Average Density (lbs. per cu.yd.)	255	750	415	736
Stops to Fill Truck	247	0	685	745
Hours to Fill Truck	2.85	0.00	5.02	4.77
Unload Time (round trip)	1.50	0.00	1.33	1.50
Start/End Route Hours	1.83	0.00	1.67	1.83
Loads per Day	1.4	0.0	1.0	1.0
Daily Drive-bys	922	0	761	784
Required Trucks	27	0	16	32
Working Hours per Truck	7.32	0.00	6.69	6.60
Truck Costs:				
• Purchase Price	$50,000	$30,000	$85,000	$100,000
• Amortization (4% & 7 years)	$8,330	$4,998	$14,162	$16,661
• Daily (260 per year)	$32	$19	$54	$64
• Daily O & M	$45	$45	$65	$65
• Daily Labor	$160	$160	$200	$200
• Administration	$59	$56	$80	$82
Truck Cost per Ton	$83	$0	$60	$56

Note: *CurbConserve* rejects separate collection of food waste for the model version described in this table due to unacceptably high relative collection costs.

collection route efficiencies as well as processing and disposal costs. Table 2 also shows model output data for number of collection trucks, and route times required to pick up and deliver recyclables, yard waste and mixed refuse as computed by the model's linear programming optimization algorithm.

Table 3 shows the optimal allocation of daily tonnage managed by privately operated buy-back, publicly funded curbside recyclables and yard waste programs, privately operated drop-site, publicly funded sorting and composting of mixed waste (MWP), and disposal. Table 3 also shows public sector per-ton costs and revenues for each waste management system component. These results reflect only public sector transactions. Privately funded management methods - buy-back and drop-site operations, self-hauled waste and self-hauled recyclables - are "free" waste management methods under the narrow public sector point of view used for the Washington state analysis.

Figure 2 shows a sensitivity analysis for the effect of disposal cost on the choice of best management methods to use for recycling and composting residential solid waste, while other factors such as materials market prices, processing costs, or participation rates are held constant. At a disposal cost of at least $50 per ton, both source separation and mixed garbage processing methods should be used in order to minimize waste management costs. At disposal costs below $50, mixed waste processing is more expensive than disposal.

Figure 3 displays the effect of disposal cost on the amount of waste that can be efficiently diverted from disposal, when materials prices are about 50 percent lower than they are in the model results shown on Table 3 and Figure 2, i.e., when materials prices are at 1990 rather than 1988 levels. When recyclables market prices are lower, private sector buy-back and drop-off facilities recover less material, and the public sector curbside recyclables program is cost-effective only if disposal costs are at least $35, up from $5 as shown in Figure 2. Yard waste recycling and mixed waste processing diversion methods are not particularly sensitive to variations in market prices.

Figure 4 shows a sensitivity analysis for the effect of material prices on the choice of best waste management methods and on the total rate of diversion from disposal when disposal costs are at least $56 per ton. This $56 figure was chosen because it is the cost for recovering one ton of recyclables and compostables by processing mixed waste. At disposal costs of $56 or more, mixed waste processing is insensitive to market price, as shown by Figure 4. Figure 4 also indicates the increased private sector recycling activity associated with higher market prices, and the consequent reduction in public sector curbside collections.

Figure 5 displays the effect material prices have on choosing between public sector source separation and centralized mixed waste processing methods, when disposal costs are in the narrow range between $50 and $56 per ton. For disposal costs in this range, market prices do determine economic viability for mixed waste processing. To simplify the analysis, private recycling is assumed not to exist. At a disposal cost of $50, a fall of about 25 percent from 1988 price levels makes mixed waste processing too costly. But a price decrease approaching 45 percent causes curbside recycling to become uneconomic. At that point, the return flow of recyclables into the mixed waste stream increases the amount of marketable material that can be recovered during mixed waste processing, which makes that recovery method again economically viable until market prices fall 55 percent below 1988 levels.

This analysis of fluctuating disposal costs and market prices suggests that communities facing high disposal costs and reasonably good materials markets should implement source separation along with mixed waste recycling and composting methods. If disposal costs are too low, then the high costs for mixed waste processing will make that management option uneconomic no matter what market prices are. On the other hand, if disposal costs are high and materials prices are expected to be very poor in the long run, then mixed waste composting may be more cost-effective than aggressive source separation of recyclable materials. The range of disposal costs and market prices in which source separation and mixed waste recovery methods are competitive with each other is too narrow to warrant consideration in a community's long-range waste management plan.

MATERIAL-SPECIFIC NET AVOIDED COSTS FOR SOURCE SEPARATED AND UNSEPARATED WASTE RECYCLING METHODS

"Avoided cost" is a concept that is increasingly being used to justify waste reduction and recycling programs. For example, in New York state it has been memorialized into a general statewide municipal law which requires communities by September 1, 1992 to adopt a law or ordinance requiring that waste left for collection or delivered by the generator to a solid waste management facility should be separated into recyclable, reusable or other components for which economic markets exist. Economic markets are defined by the law to exist whenever the full avoided costs of proper collection, transportation and disposal of source separated materials are at least as great as the cost of collection, transportation and sale of said material minus the amount received from the sale of the material.

Based on laws and regulations such as this New York state general municipal law, one can expect a good deal of inquiry into proper calculation of avoided costs for various recycling methods versus various disposal methods. The *CurbConserve* optimality model uses avoided costs to determine the least-cost integrated waste management and recycling system.

Table 4 lists material-specific public sector net avoided

Table 3

Summary of Optimized System Waste Allocations, Costs and Revenues

	DAILY TONS MANAGED THROUGH INDICATED METHOD							
Waste Component	**Buy-Back**	**Curbside Recycling**	**Curbside Yard/Food**	**Drop Site**	**MWP**	**Hand Pick**	**Disposal**	**Total Tons**
Newsprint	24	22		3	8	0	1	58
Corrugated Cardboard	0	17		3	6	0	1	26
High Grade Paper	0	1		0	0	0	0	2
Mixed Waste Paper	0	33		0	16	0	3	52
Refillable Glass Containers	0	1		1	0	0	0	3
Other Recyclable Glass	0	11		3	9	0	6	30
Aluminum Beverage Containers	1	2		0	1	0	0	4
Tin Food/Beverage Cans	0	3		0	5	0	1	9
Ferrous Metals	0	0		4	3	0	1	7
Non Ferrous Metals	0	0		1	1	0	1	2
White Goods	0	0		8	1	0	0	9
PET Bottles	0	1		0	0	0	1	1
HDPE Bottles	0	1		0	0	0	1	2
Plastic Packaging/Film	0	6		0	2	0	14	22
Other Plastics	0	0		0	1	0	4	5
Tires	0	0		0	2	0	0	2
Other Rubber Products	0	0		0	0	0	1	1
Food	0		0	0	39	0	2	41
Lawn & Garden Waste	0		109	0	23	0	3	135
Wood Waste	0	0		0	7	0	1	8
Construction/Demolition (Excl. Wood)	0	0		0	1	0	2	4
Other Organic Waste	0	0		0	42	0	5	46
Other Inorganic Waste	0	0		0	9	0	22	31
Total Daily Tons	**25**	**97**	**109**	**22**	**177**	**0**	**70**	**500**

	COSTS AND REVENUES PER TON							
Collection (Including Container Costs)		$91	$60		$65	$0	$65	$63
Processing		$22	$23		$56	$0		$29
Disposal		$0	$0				$50	$7
Less: Revenue		($70)	($5)		($8)	$0		($17)
Net Cost	**$0**	**$43**	**$78**	**$0**	**$113**	**$0**	**$115**	**$82**
Memo: Total Daily Cost	$0	$4,151	$8,518	$0	$20,051	$0	$8,048	$40,768
Memo: Annual Cost per Household	$0	$9	$18	$0	$42	$0	$17	$85

Table 4

Material-Specific Net Avoided Costs for Source Separation & Unseparated Waste Recycling Methods

	MARGINAL BENEFIT/(COST) OF AN EXTRA TON MANAGED BY INDICATED METHOD						
	Curbside Refuse		Mixed Waste Processing (MWP)	Curbside Program		Added to Curbside	
Waste Component	Without MWP	With MWP		Without MWP	With MWP	Without MWP	With MWP
Newsprint	($103)	($97)	$6	$20	$16		
Corrugated Cardboard	($103)	($84)	$19	$33	$20		
High Grade Paper	($103)	($93)	$10	$98	$88		
Mixed Waste Paper	($103)	($99)	$4	$23	$19		
Refillable Glass Containers	($103)	($106)	($3)	$47	$48		
Other Recyclable Glass	($103)	($106)	($3)	$23	$25		
Aluminum Beverage Containers	($103)	$337	$440	$997	$563		
Tin Food/Beverage Cans	($103)	($74)	$29	$45	$16		
Ferrous Metals	($103)	($64)	$39	0	0	$8	($10)
Non Ferrous Metals	($103)	$37	$140	0	0	$768	$669
White Goods	($103)	($92)	$11	0	0		
PET Bottles	($103)	($119)	($16)	$158	$174		
HDPE Bottles	($103)	($116)	($13)	$198	$211		
Plastic Packaging/Film	($103)	($135)	($32)	$158	$191		
Other Plastics	($103)	($136)	($32)	0	0		
Tires	($103)	($103)	$0	0	0		
Other Rubber Products	($103)	($133)	($30)	0	0		
Food	($103)	($96)	$8	0	0		
Lawn & Garden Waste	($103)	($98)	$5	$25	$20		
Wood Waste	($103)	($98)	$5			$3	($2)
Construction/Demolition (Excl. Wood)	($103)	($126)	($23)	0	0		
Other Organic Waste	($103)	($98)	$5	0	0		
Other Inorganic Waste	($103)	($128)	($25)	0	0		
Weighted Average			**$2**				

costs for both source separated and unseparated waste recycling methods. Net avoided cost is defined to be avoided waste collection and disposal costs minus the full costs (less revenues) of recycling or composting. The table also lists in the first two columns the public sector marginal cost for additional refuse. The first column gives additional cost for managing an extra ton of household garbage when that ton is not run through a mixed waste processing facility but is instead directly disposed. The second column lists the added system costs for an extra ton of waste when mixed waste processing is involved prior to disposal.

When an extra ton is taken straight from the garbage can to disposal, the added public sector cost is the same $103 for all waste stream materials. This $103 is related to the net cost for disposal of $115 per ton shown on Table 3 above in that the difference reflects the $12 per ton annual fixed cost for the refuse container supplied to each family. The additional costs of an extra ton of household refuse are, then, the $50 disposal cost (which includes any transfer station and transportation expenses), plus the $56 per ton collection truck cost (shown on Table 2), which is reduced to $53 per average ton disposed by households because 5 percent of household refuse is self-hauled to the disposal facility.

When unseparated waste is run through a mixed waste processing facility, added cost for an additional ton of some material is a function of the material's recovery efficiency as a recyclable, the rate at which the unrecycled portion can be converted into compost and the market value of the recovered material.

The third column of Table 4 explicitly lists the net avoided costs for mixed waste processing that account for the differences between columns one and two. For a few materials which have low combined recyclables and compost separation efficiencies, or which have low prices for recovered recyclables, net avoided costs are negative. However, because mixed waste processing operates on the entire unseparated waste stream, the decision to use this recycling method is not made on a material by material basis. It is the weighted average net avoided cost that determines whether the method is cost-effective.

The last four columns on Table 4 give material-specific net avoided costs for home collection of source separated waste materials. The first of the four columns lists curbside recycling's net avoided costs versus disposal for items collected in the three recycling bins or in the biweekly yard waste pick-up. The second column gives net avoided costs versus processing the unseparated waste before it goes to disposal. The third and fourth columns show net avoided costs versus disposal and mixed waste processing, respectively, for materials that might be added to the home collection system, assuming no change would be needed in the containers provided to households already participating in the program.

The net avoided cost of curbside recycling for a specific waste stream material depends on: 1) the price received when a source separated material is processed and marketed; 2) its collection and processing costs; and 3) the refuse collection and disposal costs saved when the material is put into recycling bins rather than garbage cans. When there is drop-site recycling, the public sector cost credit to curbside recycling for avoided refuse collection and disposal is reduced by the percentage of drop-site recycling diverted into the curbside program. Similarly, when there is self-hauling of refuse, curbside's public sector cost credit for avoided refuse collection is reduced by the percentage of mixed waste that generators take to the disposal site in their private vehicles.

The net avoided cost of curbside recycling also depends on whether mixed waste is processed to recover recyclables and compostables. For example, the value of an extra ton of corrugated being set out for curbside recycling pick-up is not as great if there is a mixed waste processing system that acts as a safety net for cardboard that is mixed in the refuse container rather than being source separated. On the other hand, the value of an extra ton of PET bottles set out for curbside recycling is greater when a mixed waste processing program is also in place. The low recyclables and compostables separation rates for mixed waste processing of PET cause a synergistic cost savings for sorting mixed waste when a ton of PET is moved out of the refuse can and into the recycling containers.

The materials included in the home collection of recyclables and lawn and garden waste all have positive net avoided costs. Except for non-ferrous metals, the waste categories excluded from home collection cannot be added on a cost-effective basis when unseparated waste is being processed for recovery of recyclables. For example, the combined recyclables and compostables separation efficiencies for wood waste in mixed waste processing make it more cost-effective to leave wood in the refuse container (at least for residential wastes that have less wood than commercial wastes) rather than source separating it. In the case of non-ferrous metals, some restriction on size would probably be necessary to fit them into the three 11-gallon containers used in the specified weekly curbside collection system. They were excluded from curbside because they were assigned separation efficiencies of zero for home separation for curbside (see Table 1). n

APPENDIX
NET AVOIDED-COST FORMULAS

The public sector waste management system marginal cost (MC) of an extra ton in the refuse can for disposal is given for each waste material by:

(1) $MC = (1 - h)\, T_d + MC_d$

where the variable T is truck collection cost per ton; the variable MC is marginal cost; the variable h is the refuse self-haul rate; and the subscript d represents the disposal method for managing municipal solid waste. MC_d is thus the marginal cost of disposal, e.g., the disposal cost of $50 shown on Table 4.

For mixed waste processing, material specific net avoided costs (NAC) are given by:

(2) $NAC_{mwp} = S_m\, P_m + S_c\, (1 - e)\, P_c + (S_m + S_c)\, MC_d - MC_{mwp}$

where P is market price; S is separation efficiency; e is the compost process mass reduction rate; the subscripts m, c and d refer respectively to mixed waste processing for recyclables, mixed waste processing for compostables, and disposal; and the subscript mwp on NAC and MC refers to the mixed waste processing method. For example, S_c is the compost process capture rate (or separation efficiency) given on Table 1 for a given waste stream material; P_m is the price given on Table 1 for a material sorted as a recyclable from mixed waste; and MC_{mwp} is the marginal cost or processing cost for mixed waste, e.g., the $40 per input ton shown on Table 2.

The marginal cost of an extra ton in the refuse can when mixed waste processing occurs prior to disposal is then given by:

(3) $MC(mwp) = MC - NAC_{mwp}$

where (mwp) refers to the presence of mixed waste processing in the integrated waste management system.

For curbside recycling, material specific net avoided costs when mixed waste processing is not available as a safety net are given by:

(4) $NAC_r = P_r - T_r - MC_r + (1 - h)\, T_d + MC_d - S_{ds}\, MC$

where the new subscripts are r for curbside recycling and ds for drop-site recycling programs.[2]

Substituting from equation (1) for MC gives:

(4') $NAC_r = P_r - T_r - MC_r + (1 - S_{ds})\, MC_d + (1 - h)\, (1 - S_{ds})\, T_d$

The net avoided cost of curbside recycling for a specific waste stream material depends on three factors: 1) the market price for that material; 2) its collection and processing costs; and 3) the collection and disposal costs saved when the material is put into recycling bins rather than garbage cans, where the extent to which public sector refuse collection and disposal costs are saved depends on the drop-site recycling rate (S_{ds}) and the refuse self-haul rate (h).

For curbside recycling backed up by a safety net of mixed waste processing, curbside's net avoided costs are given by:

(5) $NAC_r(mwp) = NAC_r + S_{ds}\ [MC - MC\ (mwp)] - NAC_{mwp}$

But $MC - MC(mwp) = NAC_{mwp}$ from equation (3) above, so that:

(5') $NAC_r(mwp) = NAC_r - (1 - S_{ds})\ NAC_{mwp}$

That is, the net avoided cost for curbside recycling with mixed waste processing as a backup disposal diversion program is NAC_r reduced by mixed waste processing's net avoided cost for that portion of a ton that would not otherwise be recycled through a drop-site program. For materials that are very valuable to a mixed waste processing program, such as aluminum in absolute terms or wood waste in relative terms, the reduction in net avoided costs for curbside can be considerable when its value is measured relative to mixed waste processing rather than disposal. For example, wood waste has a positive $3-per-ton curbside net avoided cost when mixed waste processing is not a supplemental diversion possibility, versus a negative $2-per-ton curbside net avoided cost upstream of a mixed waste processing facility.

2. Drop-site recycling rates (or separation efficiencies) in the Washington state examples were assumed equal to the residential buy-back and drop-off recycling rates shown on Table 1 except for newsprint and aluminum beverage cans. For those two materials, buy-back recycling upstream of drop-site recycling was assumed to involve 65 percent and 95 percent, respectively, of total residential buy-back and drop-off recycling. Buy-back recycling was assumed not to occur for other recyclable materials.