INFORMS Journal on Applied Analytics

Publication details, including instructions for authors and subscription information:
http://pubsonline.informs.org

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Interfaces
Vol. 37, No. 6, November–December 2007, pp. 515–525
ISSN 0092-2102 | EISSN 1526-551X | 07 | 3706 | 0515

DOI 10.1287/inte.1070.0322

Optimizing Highway Transportation at the United States Postal Service

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The United States Postal Service (USPS) delivers more than 200 billion items per year. Transporting these items in a timely and cost-efficient manner is critical if USPS is to meet its service and financial goals. The Highway Corridor Analytic Program (HCAP) is a tool that aids USPS transportation analysts in identifying cost-savings opportunities in the surface-transportation network. By using HCAP, USPS has saved millions of dollars annually.

Key words: parcel industry; transportation network; large-scale integer programming; decision-support systems.
History: This paper was refereed.

The transportation network of the United States Postal Service (USPS) is large and complex; accordingly, the transportation-planning process is an important and challenging component of USPS logistics. The recently developed Highway Corridor Analytic Program (HCAP) assists in this process. HCAP is an analytical model that aids USPS transportation analysts in identifying cost-savings opportunities within the surface-transportation network. We designed the HCAP model to solve the vehicle-routing problem with pickups and deliveries (VRP/PD) by utilizing mixed-integer programming as the underlying optimization engine. The HCAP model incorporates a graphical user interface to facilitate the modeling process. Using existing data sources, it enables USPS to identify near-term savings opportunities. We developed and fully tested the model, and then deployed it to transportation analysts in USPS headquarters and regional area offices. USPS has implemented many HCAP model recommendations and has already realized annual transportation savings of over $5 million. It is currently reviewing additional savings opportunities.

Background

USPS operates one of the largest and most complex logistics networks in the world, delivering more than 200 billion pieces of mail each year. Its surface-transportation network comprises many different networks, each designed for a specific purpose. USPS also delivers many different types of mail, including letters, flats (e.g., large envelopes for unfolded documents), parcels, and periodicals. Each type has different characteristics; these determine the processing requirements. For example, because letters, flats, and parcels have different sizes, shapes, and weights, there is a need for specialized processing operations to accommodate the differences. USPS also offers several different mail classes, including priority, first-class (overnight, 2-day, and 3-day), and standard. Each mail class has specific service standards that define its overall delivery time frame. To accommodate its various type and class options, USPS has established different transportation networks. For example, the bulk mail network transports bulk mail (e.g., standard parcels and periodicals) through bulk mail centers (BMCs); the surface transfer center (STC) consolidates mail to aggregate volumes; interplant transportation carries mail among processing and distribution centers (P&DCs); priority mail is often trucked to priority mail processing centers (PMPCs) for priority processing; and time-critical mail (e.g., express mail and some first-class and priority mail) is trucked from P&DCs to air mail centers (AMCs) to enter the air transportation network. Figure 1 shows a representative map.

USPS designed each of these transportation networks to serve a particular purpose. However, the networks do not operate in isolation; significant overlap and redundancies exist among them. For example, inter-P&DC transportation may stop at a BMC, en route between P&DCs, to get bulk mail from the origin P&DC into the bulk mail network. Similarly, STC transportation may additionally stop at P&DCs to pick up and drop off inter-P&DC mail along the STC route. These multiple, intertwined transportation networks create significant complexities and challenges to USPS transportation planning. The transportation network's vast size further complicates the planning process. On an average weekday, USPS may dispatch over 75,000 trips among over 30,000 facilities (including processing facilities, post offices, and other facilities) in its highway transportation network. USPS employs a variety of advanced analytical tools and techniques to address the challenges of managing such a large and complex network.

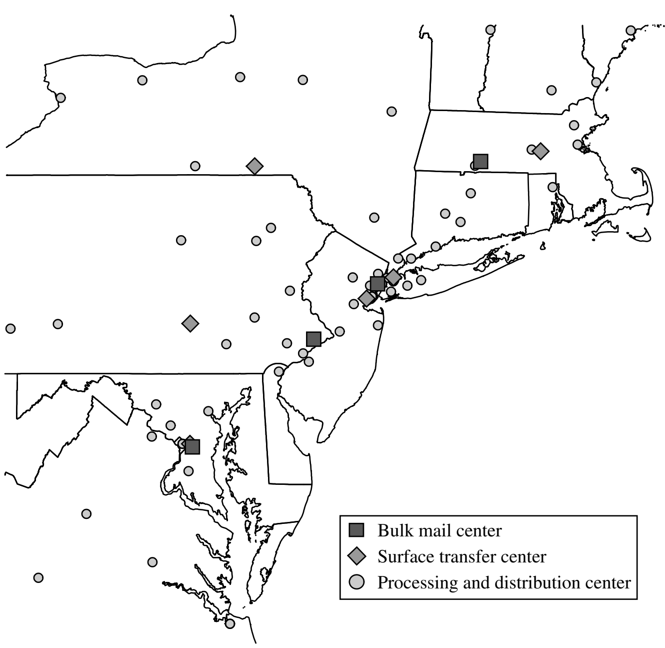

Figure 1: The map shows the general location of a sample of BMCs, STCs, and P&DCs within the USPS transportation network in the northeastern section of the United States.

Objectives

The HCAP model serves as an analytical tool to help USPS identify opportunities to reduce surface-transportation costs while maintaining on-time delivery. The tool serves and assists USPS in analyzing its surface-transportation routing and scheduling. The model is intended to be sufficiently flexible to allow USPS to apply it to a wide range of components within its transportation network. For example, USPS might apply the model to problem sets that include BMCs, STCs, P&DCs, AMCs, and a variety of other transportation applications. USPS could apply it to individual geographic regions of the nation (e.g., all processing facilities in the northeast corridor), or to a single transportation network nationwide (e.g., all BMCs), provided that the size of the network being considered is suitable for the HCAP model (see the *Modeling and Solution Approach* section for details).

Although we designed the HCAP model to be applicable to a wide variety of transportation networks, we also designed it to solve a standard problem. A problem must be defined by a set of delivery requirements among a set of facilities, and a set of feasible transportation resources to transport those deliveries. The HCAP model optimizes the transportation of the given set of delivery requirements, considering the potential transportation options that can fulfill those delivery requirements. Therefore, it is necessary to define, for each problem application, the specific delivery requirements and potential transportation options available. Delivery requirements may include both pickup and delivery requirements among a set of facilities that involves multiple types of mail with various service commitments.

The objective of the HCAP model is to optimize the existing transportation network; that is, the model identifies opportunities to modify existing USPS transportation to reduce costs. Although its objective is not to generate completely new transportation networks, the model can consider new transportation options. It is possible to generate new transportation alternatives using heuristics or operational insights, and incorporate them as potential options that the HCAP model may select when optimizing the network. The solution that the HCAP model provides will then identify the optimal set of transportation resources based on all input options provided to the model, including existing transportation and any new transportation alternatives.

Modeling and Solution Approach

The HCAP model optimizes the use of a wide variety of components within the USPS transportation network. Specifically, HCAP solves a vehicle-routing problem with pickups and deliveries (VRP/PD) model, a special instance of the more general vehicle-routing problem (VRP) model. Bodin and Golden (1981) classify various VRP problems. VRP models identify the optimal plan for routing deliveries among facilities. The underlying structure of the model consists of three primary components:

- *Facilities*: Facilities are the (generally physical) locations in the transportation network. In the HCAP model, they represent the locations (e.g., P&DCs, STCs, AMCs, and BMCs) at which mail pickups and deliveries occur.
- *Deliveries*: Deliveries are the items to be delivered between facilities. In the HCAP model, they represent the volume of mail that requires transportation from an origin to a destination facility in a specific time window (i.e., the time between the moment the mail becomes available at the origin facility and the time the mail must be delivered at the destination facility). Each delivery may likely represent a specific mail class that has a specific service standard between the origin and destination (e.g., first-class, 3-day mail from New York to San Francisco). The model considers two different types of deliveries: *splitable deliveries* can be divided into different parts for delivery, while *unsplitable deliveries* cannot.
- *Trips*: Trips are the mechanisms (routes) for moving deliveries. In the HCAP model, the trips represent the different means to transport the volume of mail from the origin to the destination facility within the required time window. Routes may be direct (from the origin directly to the destination), or multistop (stopping at one or more facilities en route from the origin to the destination). Each multistop route may pick up and/or deliver mail at any facility along its path. The definition of a trip includes every aspect of the trip: the size (capacity) of the truck, the time at which it arrives and departs at each stop, and the trip cost. It is important to note that the definition of the trips occurs prior to using the HCAP model. The set of trips is based on the existing highway transportation network, which USPS contracts primarily from independent vendors.

To model multistop trips, we use another component in the model:

Legs: Each trip consists of a series of legs between consecutive facilities visited by the trip. Direct trips have only one leg, directly from the origin facility to the destination facility. Multistop trips have more than one leg, with each leg connecting two facilities along the route's path.

Due to the nature of the USPS business, facilities can serve as both origin and destination facilities; therefore, it is possible (and almost always the case) for a single facility to dispatch and receive mail. Accordingly, a trip may include both pickups and deliveries; thus, the VRP/PD model is appropriate. Specifically, the HCAP VRP/PD model objective is to assign deliveries to trips with the following constraints:

- *Assignment constraints*: The total volume of every delivery must be routed on one or (if the delivery is splitable) more of the trips in which the delivery can be routed, i.e., the trips that can take the delivery from the delivery's origin facility to its destination facility during the delivery's time window.
- *Capacity constraints*: For every leg of every trip, the total volume associated with the deliveries routed through a trip leg must be less than or equal to the leg's capacity, i.e., the maximum volume that can be routed. The HCAP model allows the legs of a single trip to have different capacities. Therefore, in the model, USPS can consider that, by choice, some volume of mail that is *not* included as deliveries in

the model will be routed through some trip legs that *are* included in the model. For example, in a model of the southwest area, the modeler may desire to consider any excess capacity on trucks that start in the eastern area and pass through the southwest enroute to California. Mail volumes that originated in the eastern area should not be represented as deliveries within the model because they are outside the model scope (because this example is a southwest area model). However, the excess capacity of trucks entering the southwest area could be modeled by using the capacity constraints at the leg level to reflect that some of the capacity must carry the mail volumes that originate in the eastern area and are destined for various stops along the trip to California.

• *Minimal cost*: The total cost of routing the deliveries on the available trips is minimized over all the feasible assignments of deliveries to trips, i.e., that satisfy both the assignment and capacity constraints. This cost includes the fixed cost incurred for the use of any trip, and the variable cost incurred for routing the volume of the deliveries on particular legs of the trips.

We can mathematically formulate the HCAP VRP/PD model (Appendix) as a mixed-integer program (Nemhauser and Wolsey 1988). In this model, the key decisions to be made are whether or not to use each trip, and how much of each delivery to place on each accepted trip. This differs from many vehicle-routing applications where the trips are not predefined. In such cases, models need to combine legs to create trips; this is a much more complicated process. The HCAP integer program is much closer to a facility location model; Drezner (1995) presents a wide-ranging survey of location analysis that addresses all the major methods and applications in the field. This model is also very similar to the master problem in some column-generation models, such as the master problem in Desrochers et al. (1992).

There are a number of methods for finding an optimal or near-optimal solution for a VRP/PD model; these methods include commercial routing software, routing-specific software libraries, heuristic approaches, and optimization software libraries. To choose among these methods, we used the requirements described below to evaluate the alternatives.

(1) *Solution time*: The HCAP model should produce optimal or near-optimal solutions quickly. The metric we used for speed is solution time within several minutes (or seconds for smaller problems); the objective for "near optimality" is within approximately one percent of optimal.

(2) *Optimality*: Solutions must be optimal or near optimal. If they are not optimal, they should not have any "obvious" improvements, i.e., improvements that can be recognized by simple inspection.

(3) *Expandability*: While we initially designed the model for problems with a few thousand trips, future releases must be able to handle millions of trips.

(4) *Flexibility*: While the VRP/PD forms the core of the modeling approach, additional requirements on the model are inevitable. For example, after discussions with USPS, we added a feature—preferred trip for some deliveries—to the original model; this means that if a particular trip, trip A, is used, then the deliveries that have trip A as their preferred trip should be routed through that trip. This particular feature can be added to the model through additional constraints in the corresponding VRP/PD model. Therefore, the solution method must be able to handle a reasonably rich set of additional constraints.

(5) *Availability*: Initial solutions for a representative model were desired within four months of the project start date.

In view of these requirements, we decided to use the optimization software library, ILOG CPLEX, to solve the HCAP VRP/PD model. We describe the specific data needed to construct the HCAP VRP/PD model for any of the different components of the USPS transportation network in the *HCAP Model Implementation* section.

HCAP Model Implementation

We now discuss the HCAP model implementation in more detail. In particular, we discuss the specific input data required to construct the HCAP model as described in the *Modeling and Solution Approach* section and how we obtained this input data from the available USPS data. Similarly, we discuss the specific output data that we obtain by solving the HCAP model and the processing necessary to make it suitable for analysis by USPS decision makers.

Preprocessing

There are many different ways to define a problem for the HCAP model. For example, we can define it as a set of different mail processing centers that are geographically close to each other. We can also define it as a particular network, e.g., the BMC network. Once we have defined the problem, but prior to running the optimization model, it is necessary to transform the initial data into the data sets that the optimization model requires as input. This preprocessing step, which involves analysis and cleansing of the data, prepares the input data files based on the optimization model requirements for content, structure, and format. During preprocessing, the data is thoroughly examined; any inaccuracies and inconsistencies are identified and corrected. The preprocessing step is critical in model development because the model input data directly impacts the model output results. This section briefly describes the preprocessing step relative to deliveries, and the trips considered in a particular instance.

- *Deliveries*: The goal of the deliveries preprocessing step is to identify the parameters necessary to define a delivery, and generate a standardized data set as output for use in the optimization model (see the *Optimization Model Inputs* section). To obtain all the parameters, we extracted data from USPS systems. These included the National Air and Surface System (NASS), the Transportation Information Management Evaluation System (TIMES), and the Transportation Contract Support System (TCSS). We also collected data from USPS subject matter experts (SME). Figure 2 shows a summarized flowchart of the process to complete the *Deliveries* preprocessing.
- *Trips*: The goal of the trips preprocessing step is to identify the parameters necessary for defining a trip (cf. the *Optimization Model Inputs* section), and generate a standardized data set as output for use in the optimization model. The trips may be either existing or newly created. To satisfy all the parameters, we extracted data from USPS systems (NASS, TIMES, and TCSS); we also collected data from USPS SMEs. Figure 3 shows a summarized flowchart of the process to complete the *Trips* preprocessing.
- *Delivery-trips cross-reference*: Prior to running the optimization model, it is necessary to run a preprocessing step to identify the trips that are feasible for each delivery. A trip is deemed feasible if it departs from the origin at or after the delivery's available time and arrives at the specified destination at or before the delivery's required time. The feasible trips identified for a delivery correspond to the trips from which the optimization can choose to transport that delivery.

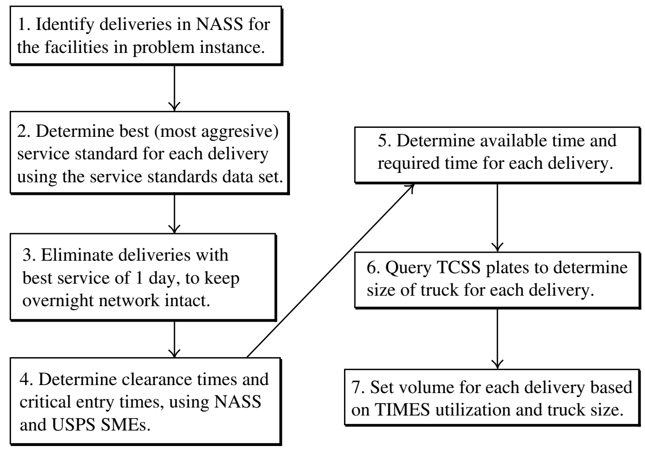

Figure 2: The delivery preprocessing flowchart defines the parameters of each delivery.

Optimization Model Inputs

As previously discussed, the three underlying components of the HCAP model structure are facilities, deliveries (i.e., mail volumes between pairs of facilities), and trips among the facilities. The optimization model (*Modeling and Solution Approach* section) requires the following specific inputs to define an instance of the HCAP model.

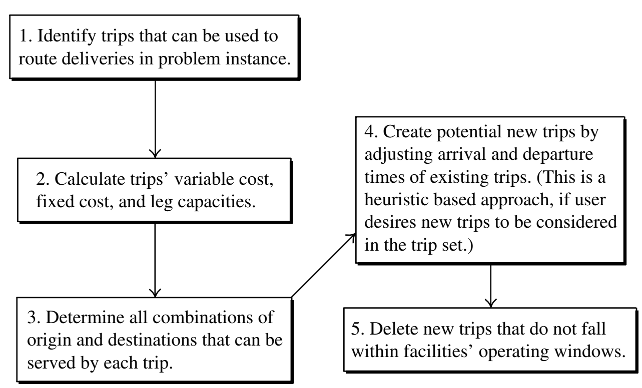

Figure 3: The trips preprocessing flowchart defines the parameters for each trip.

• *List of facilities*: The facility list identifies all facilities to be included in the analysis. The HCAP model can handle many different types of facilities, e.g., PDCs, BMCs, PMPCs, AMCs, STCs, major mailers, and others. The set of facilities included within a single analysis, however, should be chosen such that it represents a logical component of a transportation network. In other words, the pickup and delivery relationships between all facilities in the facility list should make sense, and the interrelationships among facilities should be well defined. Depending on the nature of the transportation network, each facility may serve an origin facility, a destination facility, or both. The characteristics that differentiate origin and destination facilities are specified in the data inputs for deliveries between facility pairs.

• *List of deliveries between facility pairs*: The HCAP model optimizes the selection of trips among facilities to minimize the total transportation costs while meeting all delivery requirements. We define each delivery as a specific volume of mail that requires transport from an origin facility to a destination facility. The HCAP model uses the following characteristics:

—The origin facility (the location at which the mail is to be picked up).

—The time at which the mail is available at the origin facility.

—The destination facility (the location to which the delivery must be made).

—The time at which the delivery is required at the destination facility.

—The volume of the delivery.

—Whether or not the delivery is splitable (see the *Deliveries* item in the *Modeling and Solution Approach* section).

Note that, in practice, different mail classes may have different available times or different delivery-time requirements. Therefore, we may define separate deliveries for each mail class. For example, for the mail going from a single origin facility to a single destination facility, we may define different deliveries for each mail class—first-class, priority, standard, and packaged services. However, it may be possible (and preferable) to combine multiple mail classes into a single delivery in cases where they share the same availability time and the same required delivery time for a specific origin-destination pair.

• *Feasible trips among facilities*: Each delivery specifies a volume of mail that must be transported from a specific origin facility to a specific destination facility within a certain time window. For each delivery, there are certain existing trips and a potential number of new (but defined) trips that could transport the mail from the origin facility to the destination facility. These trips may travel directly from the origin to the destination (i.e., a one-leg trip), or they could stop at one or more other facilities along the way (i.e., a trip with various legs). For each delivery, a set of feasible trips (i.e., the set of all possible trips in which the delivery can be transported from the origin to the destination within the delivery's time window) must be specified. For each of these feasible trips, we must provide the following characteristics:

—The origin facility.

—The destination facility.

—All stops (i.e., legs) along the trip between origin and destination.

—The transportation capacity on each leg along the trip.

—The fixed transportation cost of the trip.

—The variable transportation cost (i.e., cost per unit of volume) on each leg along the trip.

Trips generally will have the same capacity on all legs along the trip because the truck size will remain unchanged. However, as previously discussed (see *Capacity constraints* in the *Modeling and Solution Approach* section), different leg capacities might be used to take into account mail deliveries that are not in the model but have been already assigned to some of the trip legs. Variable cost may also be the same on all legs along the trip, or variable cost may often be zero if the cost structure is such that the trip incurs a single fixed cost (possibly based on mileage of the trip) for utilizing the trip.

• *Baseline scenario*: To evaluate the cost-saving opportunities that the HCAP model has identified, the user can (and typically does) input a baseline scenario, i.e., the assignment of deliveries to trips currently being used to route the deliveries of interest through the USPS transportation network (see the *Optimization Model Outputs and Postprocessing* section for details).

Solution of the HCAP VRP/PD Model

We developed a C++ program that reads the information in the optimization model inputs and constructs the HCAP VRP/PD MIP (see the *Modeling and Solution Approach* section) such that it can be solved by the CPLEX optimization library. This code also generates the relevant optimization model outputs from the CPLEX solution information.

Optimization Model Outputs and Postprocessing

The optimization model identifies the optimal set of trips that can satisfy all delivery requirements. Therefore, the output that this model generates is the subset of trips that an optimized scenario should utilize and the optimal assignment of each delivery to the appropriate trip(s). The optimization model also returns the total transportation cost for the optimal assignment. The HCAP model postprocesses this raw output information to produce several final reports for USPS decision makers to analyze. In addition to the optimization model inputs and outputs, mapping files are used to associate the deliveries and trips with NASS-specific information and to link the deliveries to their assigned trips.

• *Cost summary report*: The cost summary report summarizes the potential cost savings that USPS could realize by implementing the optimized trip recommendations that the HCAP model identified. These cost savings represent the potential annual decrease in transportation costs for the set of transportation modeled, as the result of trip consolidation opportunities. Figure 4 shows a sample cost summary report.

In particular, this report shows the annual transportation costs associated with the baseline scenario, the annual costs associated with the optimized transportation network, and the corresponding annual savings attainable by implementing the model recommendations. The indemnity cost is the penalty that USPS would have to pay for early termination of established contracts; the model considers this penalty when identifying the optimal solution. The estimated first-year savings represent the expected annual savings, considering any penalty costs for indemnity.

• *Operational summary report*: The operational summary report shows the number of trips in the scenario, the number of trips recommended for elimination (by consolidating their mail volumes onto other trips), and the number of remaining trips that have mail added to them (from the eliminated trips). Figure 5 shows sample information from this report.

We calculate these numbers by comparing the trips in the baseline set with the trips in the optimization results to determine the number of trips that we could eliminate through consolidation.

• *Utilization summary report*: The utilization summary report displays the change in average trip utilization that would result by implementing the

	A	B	C
1	USPS Highway Corridor Analytic Program		
2	Scenario (PACIFICSUBSETFORDEMO0214)		
3	Created on 01-20-2007 at 15:19		
4	Cost summary report		
5			
6	**Cost_summary**	**Cost**	
7	Original estimated annual cost	$1,426,069	
8	Potential estimated annual cost	$860,553	
9	Total potential estimated savings (not considering idemnity)	$565,516	
10	Estimated indemnity	$16,148	
11	Estimated first year savings (considering idemnity)	**$549,368**	
12			

Figure 4: The table shows a sample cost summary report (formatted for display purposes).

	B	C	D
1	USPS Highway Corridor Analytic Program		
2	Scenario (PACIFICSUBSETFORDEMO0214)		
3	Created on 01-20-2007 at 15:21		
4	Operational summary report		
5			
6	**Operational_summary**	**Trips**	
9	Total number of trips in scenario	46	
13	Number of trips recommended for elimination	**16**	
14	Number of trips with volume added	14	
16	Number of trips not adjusted in model run	16	
17			

Figure 5: The table shows a sample operational summary report (formatted for display purposes).

	A	D	E
1	USPS Highway Corridor Analytic Program		
2	Scenario (PACIFICSUBSETFORDEMO0214)		
3	Created on 01-20-2007 at 15:20		
4	Utilization summary report		
5			
6	**Utilization_Summary**		
7	Original average utilization	63%	
8	New potential average utilization	85%	
10	Number of trips with an increase in utilization	13	
11	Number of trips with a decrease in utilization	0	
12	Number of trips with no change in utilization	17	
13		.	

Figure 6: The table shows a sample utilization summary report (formatted for display purposes).

optimization results. Increased utilization is typically desirable because low utilization often indicates excess capacity that is paid for but is not being used to transport mail volumes. As this report shows, by consolidating mail onto fewer trips through optimization, the average utilization on the trucks being used typically increases. Figure 6 shows a sample utilization summary report.

We calculate the *original average utilization* by dividing the mail volumes on current (baseline) trucks into the capacities of those trucks; similarly, we calculate the *new potential average utilization* for the optimized set of trucks by dividing the assigned volumes by capacities for that optimal set of trucks.

• *Operational detail report*: While the summary reports present information about overall statistics, such as potential annual costs savings, trip-elimination counts, and average utilization-improvement percentages, the operational detail report details how the transportation specialists would actually implement the results recommended by the optimization output. This report displays each existing truck (from the baseline) side-by-side with the optimal assignment (i.e., how specifically the mail that is currently being transported on that truck should be transported within the optimized condition). In many cases, the current truck remains within the optimized set and the optimal recommendation is merely to continue transporting that truck's volume on that truck. In other cases, the truck can be eliminated and its mail consolidated onto another truck that has excess capacity. In such a situation, the right side of the report shows the new truck assignment that replaces the existing truck assignment shown on the left side. Figure 7 displays sample information from a subset of the operational detail report. We have modified the data in the report to protect USPS privacy. For display purposes, we have reformatted the report such that the current trip is displayed in gray and the recommended trip is displayed in white below the current trip, rather than to the right of the current trip. We have used arrows to highlight the consolidation opportunities.

Results

We have fully developed and tested HCAP and have deployed it to transportation analysts at USPS headquarters and regional area offices. These analysts are currently using HCAP to optimize transportation subsets throughout the United States to identify cost-savings opportunities. The model provides each analyst with flexibility to define specific scenarios of interest, set the business constraints and model parameters, and analyze the results to develop implementation recommendations. The analysts have already completed several sample HCAP scenarios and have either implemented many of the recommendations or are in the process of doing so.

During HCAP development, personnel at USPS headquarters, the Pacific area office, and IBM worked together to model the Pacific area transportation network, including transportation among P&DCs, BMCs, AMCs, and STCs. Many of the recommendations from this model run have already been implemented; the resulting savings have been approximately \$3.7 million annually to date. These savings represent 24 percent of the transportation costs that were eligible for elimination within the optimization model run. (In each model run, a portion of the trips are eligible for elimination; eligibility depends on trip-data availability and user-specified parameters.)

We developed a separate scenario for inbound and outbound transportation at an STC in the midwest. Implementing the recommendations from that model run has resulted in approximately \$1.3 million in annual savings to date. USPS also used the HCAP model in the eastern area, adapting it to model local transportation at a North Carolina P&DC and STC transportation in Pennsylvania. HCAP helped

	A	B	C	D	E	F	G	H	I	J	K
1	USPS Highway Corridor Analytic Program										
2	Scenario (PACIFICSUBSETFORDEMO0214)										
3	Created on 01-20-2007 at 15:26										
4	Operational detail report										
5											
6			**Contract**	**Trip**	**Origin facility**	**Departure**	**Destination facility**	**Arrival time**	**Util**	**Est. cost**	
7						**Time**					
8		*Baseline*	923A6	105	SANTA BARBARA P&DC	1325	LOS ANGELES BMC	1505	0.3%	$57,571	
9		*Solution*	900Q7	604	SANTA BARBARA P&DC	415	LOS ANGELES BMC	545	73%		
10											
11		*Baseline*	923A6	106	LOS ANGELES BMC	1230	SANTA BARBARA P&DC	1430	60%	$57,571	
12		*Solution*	900Q7	605	LOS ANGELES BMC	105	SANTA BARBARA P&DC	230	19%		
13											
14		*Baseline*	923A6	104	LOS ANGELES STC	1040	SANTA BARBARA P&DC	1220	74%	$51,175	
15		*Solution*	923A6	104	LOS ANGELES STC	1040	SANTA BARBARA P&DC	1220	74%		
16											
17		*Baseline*	948RT	419	STOCKTON P&DC	345	SAN FRANCISCO P&DC	500	24%	$64,526	
18		*Solution*	950CC	105	STOCKTON P&DC	400	SAN FRANCISCO P&DC	510	61%		
19											
20		*Baseline*	948RT	420	SAN FRANCISCO P&DC	500	STOCKTON P&DC	615	43%	$64,526	
21		*Solution*	948RT	404	SAN FRANCISCO P&DC	745	STOCKTON P&DC	900	50%		
22											
23		*Baseline*	948RT	421	STOCKTON P&DC	2045	SAN FRANCISCO P&DC	2200	90%	$72,925	
24		*Solution*	948RT	421	STOCKTON P&DC	2045	SAN FRANCISCO P&DC	2200	90%		
25											
26		*Baseline*	948RT	422	SAN FRANCISCO P&DC	2345	STOCKTON P&DC	100	85%	$72,925	
27		*Solution*	948RT	422	SAN FRANCISCO P&DC	2345	STOCKTON P&DC	100	85%		
28											

Figure 7: The optimization identified an opportunity to consolidate trip #105 of contract 923A6 onto trip #604 of contract 900Q7. Elimination of this trip would save $57,571 annually (minus any applicable indemnity penalty).

to identify approximately $400,000 annual savings in those efforts. Several other scenarios are currently in development at various other area offices as well as at USPS headquarters. In these scenarios, transportation analysts are exploring many different applications of the model, including using HCAP for renewal period analysis (i.e., identifying which trips should be renewed and which trips may be consolidated with other trips), planning for the holiday peak season, and helping identify alternative solutions in STC transportation planning.

Conclusion

USPS operates an extremely large and complex transportation network; accordingly, transportation planning is a critical and challenging component of its logistics. USPS is proactively developing a comprehensive set of analytic capabilities, using advanced modeling techniques, to assist in its transportation-planning process. HCAP is an optimization model that USPS and IBM designed and developed to identify savings opportunities in the USPS highway transportation networks. We tested and developed the HCAP model, and deployed it to transportation analysts at USPS headquarters and regional area offices. USPS has used HCAP to model many different subsets of USPS highway transportation, has implemented many of the model results, and has already realized significant annual savings.

Appendix

Mathematical Formulation of the USPS HCAP Problem

The HCAP mathematical programming formulation uses the following basic model variables and parameters:

Index Sets

$\mathcal{I}$ set of all deliveries.
$\mathcal{R}$ set of all trips.
$\mathcal{K}_r$ set of all legs on trip $r \in \mathcal{R}$.
$\mathcal{U}$ set of all unsplitable deliveries (i.e., deliveries that must be routed on a single trip).

Parameters

V_i volume of delivery $i \in \mathcal{I}$.
F_r fixed cost for using trip $r \in \mathcal{R}$.

C_{rk} cost per unit of volume routed on leg $k \in \mathcal{K}_r$ of trip $r \in \mathcal{R}$.

S_{rk} capacity (in units of volume) of leg $k \in \mathcal{K}_r$ of trip $r \in \mathcal{R}$.

A_{ir} 1 if delivery $i \in \mathcal{I}$ can be routed on trip $r \in \mathcal{R}$. 0 otherwise.

B_{irk} 1 if $A_{ir} = 1$ and delivery $i \in \mathcal{I}$ uses leg $k \in \mathcal{K}_r$ of trip $r \in \mathcal{R}$ when routed on trip r, 0 otherwise.

Variables

y_r 1 if trip $r \in \mathcal{R}$ is used, 0 otherwise.

x_{ir} proportion of delivery's $i \in \mathcal{I}$ volume that is routed using trip $r \in \mathcal{R}$.

Basic MIP Formulation

$$
\begin{aligned}
\text{Minimize} \quad & \sum_{r \in \mathcal{R}} \left(F_r y_r + \sum_{k \in \mathcal{K}_r} \sum_{i \in \mathcal{I}} B_{irk} C_{rk} V_i x_{ir} \right) \\
\text{subject to} \quad & \sum_{r \in \mathcal{R}} A_{ir} x_{ir} = 1 \quad \forall i \in \mathcal{I}, && \text{(C.1)} \\
& \sum_{i \in \mathcal{I}} B_{irk} V_i x_{ir} \le S_{rk} y_r \\
& \qquad \forall r \in \mathcal{R}, \forall k \in \mathcal{K}_r, && \text{(C.2)} \quad (1) \\
& x_{ir} \le y_r \quad \forall r \in \mathcal{R}, \forall i \in \mathcal{I}, && \text{(C.3)} \\
& 0 \le x_{ir} \le 1 \quad \forall r \in \mathcal{R}, \forall i \notin \mathcal{U}, && \text{(C.4)} \\
& y_r \in \{0, 1\}, \quad x_{ir} \in \{0, 1\} \\
& \qquad \forall r \in \mathcal{R}, \forall i \in \mathcal{U}. && \text{(C.5)}
\end{aligned}
$$

The objective of this MIP formulation is to minimize the total cost of routing the deliveries on the available trips. This cost includes the fixed cost incurred for the use of any trip and the variable cost incurred for routing the volume of the deliveries on particular legs of the trips. Constraint (C.1) ensures that 100 percent of every delivery's volume is routed on one or (if the delivery is splitable) more of the trips in which the delivery can be routed. Constraint (C.2) ensures that the total volume routed on all legs of the trips used (i.e., when $y_r = 1$) is less than or equal to the capacity of the legs. The right side of (C.2) makes the capacity of legs in unused trips (i.e., when $y_r = 0$) equal to zero. We multiply the leg capacities by the trip variables in the right side of (C.2) to strengthen the MIP formulation of the problem. Constraint (C.3) ensures that deliveries (or percentages of deliveries) are routed only on trips used.

Strengthening Constraints

To further strengthen this MIP formulation, we incorporated two major types of constraints into the formulation:

(1) *Symmetry breaking constraints*: To construct the MIP formulation (1), it is necessary to generate the trips in advance (as opposed to other vehicle-routing applications, such as that of Desrochers et al. 1992, which generate trips as needed). Given that it is unclear exactly what trips the formulation will need, it is likely that multiple similar trips will be added to the formulation. These trips can hopelessly slow down a MIP solution by requiring it to explore and eliminate many alternative, equivalent solutions—so-called *symmetric solutions* (Sherali and Smith 2001). To avoid this problem, we rank trips as follows: Consider two specific trips; for example, trip A and trip B. If

(a) the fixed cost of trip A is less than or equal to the fixed cost of trip B, and

(b) the variable cost (per unit of volume routed) of each leg of trip A is less than or equal to the variable cost of trip B, and

(c) the set of deliveries that can be routed on trip B is a subset of those that can be routed on trip A, then we say that trip A dominates trip B. If trip A dominates trip B and trip B dominates trip A, then trips A and B are equivalent. If trip A dominates trip B, we can add the constraint $y_A \ge y_B$ to the basic MIP formulation of Equation (1) without deleting any optimal solutions. In doing so, we remove the symmetry between trip A and trip B, making the solution process much more efficient. If trips A and B are equivalent, we can break the tie arbitrarily, as long as we do it consistently. In practice, we break ties in order of appearance in the input data file.

(2) *Knapsack constraints*: Consider any set of deliveries $\mathcal{D} \subseteq \mathcal{I}$. Let $\mathcal{R}(\mathcal{D})$ be the set of trips in which at least one of the deliveries in $\mathcal{D}$ can be routed. For each trip r in $\mathcal{R}(\mathcal{D})$, let S_r^* be the maximum capacity of any leg of trip r that can be used by a delivery

in $\mathcal{D}$. Then, the knapsack constraint (Nemhauser and Wolsey 1988)

$$\sum_{r\in\mathcal{R}(\mathcal{D})} S_r^* y_r \geq \sum_{i\in\mathcal{D}} V_i$$

is a valid constraint for this problem. As given, this constraint does not strengthen the formulation. However, modern integer-programming optimizers recognize the form of this constraint and are able to add cover inequalities (Nemhauser and Wolsey 1988) and other constraints to strengthen the integer program. These redundant constraints generally create models that are easier to solve (Aardal 1998). There are a number of choices to construct sets $\mathcal{D}$; for example, $\mathcal{D}$ can be the set of all deliveries that have the same origin and destination. In practice, we add a knapsack constraint to the basic MIP formulation of Equation (1) for every set $\mathcal{D}$ corresponding to an origin-destination pair in the problem. The computational testing that we did confirms the findings of Aardal (1998): the addition of these seemingly redundant constraints is key to the effective solution of this model.

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Calvin Williams, Manager, Network Optimization, United States Postal Service, 475 L'Enfant Plaza SW, Washington, DC 20260, writes: "I have reviewed the manuscript 'Optimizing highway transportation at the United States Postal Service' and verify its accuracy."