UTILIZING SCHOOL BUS ROUTES TO DELIVER MEALS TO FAMILIES IN NEED

Stephen F. Smith (PI), https://orcid.org/0000-0002-7053-3166
Karen Lightman,
Zachary B. Rubinstein, https://orcid.org/0000-0002-6344-8692
Ashley Li, https://orcid.org/0000-0001-7211-2018

FINAL RESEARCH REPORT

Contract # 69A3551747111

Utilizing School Bus Routes to Deliver Meals to Families in Need

Final Report

Stephen F. Smith (PI), Karen Lightman, Zachary B. Rubinstein and Ashley Lee

Carnegie Mellon University

Overview

This report summarizes the results of a 3-month project aimed at coupling AI-based routing and scheduling technology with machine learning to demonstrate an initial solution to the problem of remote delivery of school meals to students in need, and jumpstarting research in this area. With the onset of the COVID19 pandemic, K-12 school meal programs have been unexpectedly disrupted, raising the need for alternative remote delivery processes. Working together with Allies for Children, a local non-profit organization, and the Penn Hills School District, we developed intelligent delivery-location selection along with initial route optimization algorithms and applied them to produce a set of vehicle delivery routes aimed at providing meals to those students in greatest need, while satisfying remote food delivery and social distancing constraints. Delivery vehicles began driving these routes as Penn Hill's summer school delivery program in July 2020. As of early August, over 5000 school meals have been delivered, and plans are in place to transition this remote meal delivery program into the fall. In the sections below, we summarize the problem, our technical approach and results obtained to date.

Problem

One important consequence of the onset of the COVID-19 pandemic last spring has been disruption to K-12 school meal programs. Over 13 million low-income students nationwide rely on their school to provide daily meals [Hobbs20], and, with the closing of schools, this service is no longer being provided. To address this problem, school districts across the nation have been experimenting with ways to repurpose school buses to deliver school meals to the students (e.g., [Coco20, Gannon20, Hobbs20, Marohn20]). The basic strategy has been for buses to simply drive their usual routes and deliver food to students at their bus stops instead of picking them up. However, these routes were developed under different assumptions and optimization objectives. The remote school meal delivery problem has somewhat different requirements and constraints, and even though use of these routes provides a baseline initial solution, there are great opportunities for achieving more effective and more efficient solutions.

In brief, the remote meal delivery problem involves (1) determining a set of drop-off locations and (2) generating a set of vehicle itineraries that collectively visit each drop-off location once. Each vehicle must stop for a fixed duration at each of the drop-off locations in its itinerary, and all drop-off locations must be visited within a specified meal time interval. There is a single location where all vehicles pick up meals for delivery, a single location where all vehicles return any extra meals after completing their respective itineraries. The objective is to maximize the expected number of meals that are delivered.

Technical Approach

Our technical approach has followed contemporary trends in school bus routing research toward consideration of more complex, real-world problem formulations and the development of scalable meta-heuristic solutions to them [Schittekat13, Ellegood19]. The combined problem of bus stop assignment and route generation has long been known to be NP-hard [Laporte88], and like most previous work on these types of problems, our solution approach considers these two subproblems sequentially and independently. For selection of drop-off locations (the first subproblem), proximity-based clustering is applied to student home locations to estimate the number of meals that would be picked up at a given candidate stop, and the overall set of existing bus stops are evaluated to determine the highest payoff subset of stops. For vehicle assignment and routing (the second subproblem), we have adapted incremental and iterative constraint-based search procedures that have proved effective in our previous work on other related scheduling and routing problems [Smith04, Kramer07, Rubinstein12, Kinable16]. The resulting composite algorithm is summarized below in Figure 1. We also developed a constraint programming solution to the second subproblem, both to provide a concise formulation of this problem and, through extended computation with IBM's CP Optimizer tool (https://www.ibm.com/analytics/cplex-cp-optimizer), a benchmark for evaluating the effectiveness of our heuristic solution. This CP formulation is included as an Appendix to this report.

Figure 1: Initial Heuristic Routing Algorithm

1. Incrementally generate an initial set of vehicle routes by:
    a. Compute number of remaining unserved students within walking distance w from each remaining candidate bus stop.
    b. Choose stop s that services the most students, and assign that stop to one of the m delivery routes.
    c. Remove the students serviced by this stop from the set of remaining unserved students and remove stop s
    d. Repeat steps a-c until either
        i. All students are served,
        ii. The meal carrying capacity of all vehicles is reached, or
        iii. No additional fixed duration stops can be fit within the meal delivery time window.
2. Iteratively swap pairs of stops between routes to further reduce vehicle travel times.

Application

Our focus on this problem originated through discussions with Allies for Children, a local nonprofit organization focused on the welfare of K-12 school children. In early 2020, We began a collaborative project with Allies through the Metro21 Institute at CMU, aimed at consolidating bus routes across school districts for student transport to non-public and charter schools. When the COVID19 pandemic hit and schools closed, Allies came to us to see if there was anything we might be able to do to help address the food security issue that economically depressed school districts in the region now faced. Startup funding was obtained from the sister CMU Traffic21 Institute to help demonstrate a remote food delivery solution. The Penn Hills school district, which was already intent on establishing a summer school lunch delivery program, was chosen as the demonstration focus.

To provide a basis for analysis and experimentation, the Penn Hills School district provided the following two basic data sets:

- The home addresses of all 3209 K-12 public school students living in the Penn Hills school district (anonymized)
- The set of 233 existing bus stop locations for pickup and drop off of Penn Hills public school students

Data on the Penn Hills road network was extracted from the Open Streets Map Data service, and used (along with projected vehicle speed information) to produce a point-to-point travel duration matrix between all locations of interest, including the set of existing bus stops, the initial meal pickup location and the final leftover meals drop off location.

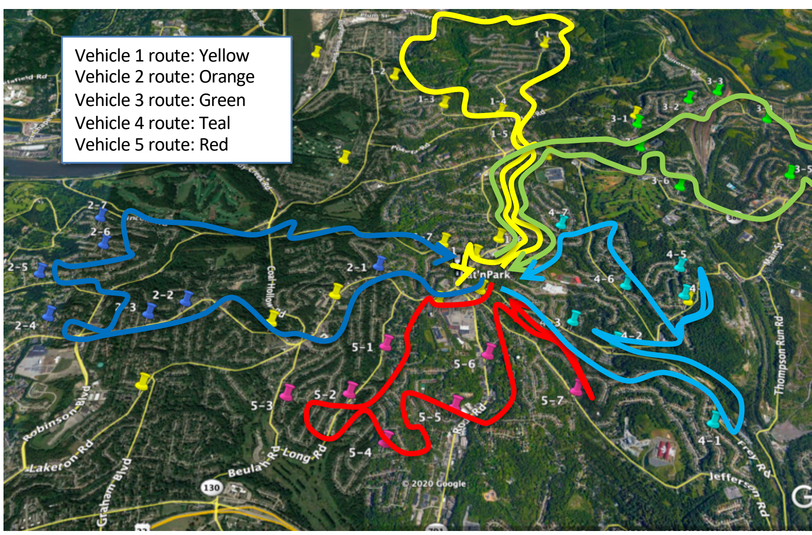
Finally, other relevant constraints such as maximum allowable student walk distances, delivery stop durations, and minimum and maximum constraints of number of students serviced at a given delivery stop were determined through discussions with Penn Hills and Allies for Children personnel.

Implementation

As summer 2020 approached, concrete plans were put in place for implementing the summer school meal delivery program. Eat’n Park Restaurant agreed to provide the meals and became the food pickup location. Use of the Penn Hills school buses for delivery proved to not be viable, but funding from the United Way of Western Pennsylvania enabled contracting of five vans and drivers from ACCESS Transportation Systems, the paratransit organization that services Allegheny County.

Using the meal carrying capacity constraints associated with the ACCESS vehicles, the algorithm sketched in Figure 1 was applied to the Penn Hills data summarized above to generate a set of feasible delivery routes that maximized the number of "expected" meals delivered. The constraints enforced included a ¼ mile maximum student walking distance (from home to delivery stop), a 15 minute stop duration at each stop location, and a minimum bound of 10 in-range students for a given stop to be viable.

Once routes were generated, each was physically driven to determine whether there were any factors not considered by our model (such as heavy traffic or no parking space) that could impact the safety of delivering meals at the chosen stops. A few stops were found to have such problems, and in these cases, the problematic stop was eliminated as a candidate stop, and a new nearby stop was substituted. For purposes of determining how many meals each vehicle should carry, an assumption was made that 50% of the students determined to be serviceable by a given stop would actually show up (with the assumption that the number of meals carried would be adjusted as experience was gained). The final summer meal delivery routes that were used are shown in Figure 2.



VEHICLE ID	ADDRESS	EST	LST	EFT	LFT	NUMBER SERVED
1	HAMIL RD AND VALEMONT DR	1100	1100	1115	1115	21
1	7194 SHANNON RD	1121	1121	1136	1136	29
1	SHANNON RD AND SHANNON HEIGHTS DR	1138	1138	1153	1153	13
1	HULTON RD AND HAMIL RD	1154	1154	1209	1209	21
1	SALTSBURG RD AND MCGREGOR DR	1210	1210	1225	1225	10
1	FRANKSTOWN RD AND PARKRIDGE DR	1228	1228	1243	1243	30
1	LIME HOLLOW RD AND ALTHEA DR	1244	1245	1259	1300	18
2	FRANKSTOWN RD AND JANICE DR	1100	1102	1115	1117	25
2	9915 FRANKSTOWN RD	1118	1120	1133	1135	54
2	FRANKSTOWN RD AND CHAMPA STREET	1134	1136	1149	1151	24
2	EASTWOOD RD AND UPLAND TERRACE	1151	1153	1206	1208	29
2	MT CARMEL RD AND CALMAR DR	1208	1210	1223	1225	23
2	GROVE RD AND MARK DR	1225	1227	1240	1242	47
2	GROVE RD AND SELVIN DR	1242	1245	1257	1300	31
3	LEECHBURG RD AND GARDEN DR	1100	1101	1115	1116	18
3	NASH AVE AND SUTTON DR	1116	1118	1131	1133	11
3	LEECHBURG RD AND BARCKHOFF ST	1132	1134	1147	1149	28
3	UNIVERSAL RD AND MEADOW DR	1149	1151	1204	1206	10
3	WOODSTONE DR AND DEERWOOD DR	1207	1209	1222	1224	20
3	ALCOMA DR AND TUNNELVIEW DR	1225	1227	1240	1242	23
3	225 ALCOMA BLVD	1243	1245	1258	1300	15
4	LAURIE DR AND LOMOND DR	1100	1100	1115	1115	18
4	FREY RD AND WHITES LN	1117	1118	1132	1133	26
4	715 UNIVERSAL RD	1134	1134	1149	1149	64
4	ANTHON DR AND ANGE DR	1152	1153	1207	1208	51
4	ANTHON DR AND CHARLESTON DR	1208	1208	1223	1223	12
4	STOTLER RD AND BALE DR	1226	1226	1241	1241	33
4	SHENANDOAH DR AND YOSEMITE DR	1244	1245	1259	1300	35
5	LONG RD AND JOAN DR	1100	1101	1115	1116	35
5	LONG RD AND ROSEWOOD DR	1116	1117	1131	1132	46
5	MACFARLANE DR AND PENN VISTA DR	1132	1133	1147	1148	22
5	MARSHALL DR AND MAROSE DR	1151	1152	1206	1207	39
5	698 NEWPORT DR	1208	1209	1223	1224	13
5	375 RODI RD	1225	1226	1240	1241	17
5	JEFFERSON HEIGHTS RD AND LEWIS RD	1243	1245	1258	1300	39
					Total Served:	950

Figure 2: Summer meal delivery program vehicle routes.

The above routes were first driven on July 3, 2020. Allies for Children provided yard signs to identify the bus stops and printed handouts that were delivered in advance to other food pickup/pantry locations. Social network and media outlets were also used to help spread the word. Based on feedback from our partners, it was quickly realized that students were not identifying the ACCESS shuttles as the vehicles that were carrying the meals. In response, secured magnets were subsequently acquired to put on the sides of the vehicles to help promote and advertise.

Overall, the prototype implementation has been considered successful by all stakeholders. As of early August, over 5000 school meals had been delivered, and it has recently been named as Metro Lab Network's "Innovation of the Month" for August 2020 (https://metrolabnetwork.org/projects/innovation-of-the-month/). Some pictures of the school lunch delivery program in action are given in Figures 3,4, and 5.

Figure 3: Marked delivery vehicle and driver

Figure 4: Delivery of meals to families in need

Figure 4: Two students receiving meals

In mid-August, the routes were tweaked slightly in anticipation of the approaching fall school semester, removing 4 stops that received very few customers and replacing them with 4 more promising locations. Current school district plans call for startup with virtual instruction and continuation of the home school meal delivery program through the fall of 2020.

Next Steps and Broader Impact

The success we have achieved with Penn Hills has attracted the attention of other school districts and we are currently investigating application of our technology more broadly in the greater Pittsburgh region. We have recently used our machine learning analysis tools to identify new candidate stops for extending existing routes being driven by the Greater Pittsburgh Food Bank in the McKeesport area to enable student meal delivery to high need areas. Interaction with several additional school districts is also under consideration.

We have also received additional funding through the National Science Foundation (NSF) RAPID program to undertake a more systematic investigation of these new classes of the vehicle routing problem, with the goal of providing new problem formulations and reference problems to spur further research in this area.

Finally, the Principal Investigator is also co-PI of a recently awarded proposal to NSF's Cyber-Physical Systems program that is focused on techniques for discovery of anomalies (construed broadly as unusual events) from video and image data, and their subsequent resolution. One general application area of interest in this work is using machine learning based analysis of recorded video to identify factors of potential delivery stops (e.g., presence of nearby parking lot) that are not discernable from existing data.

References

[Coco20] Coco, C., "Hamilton County School Buses Deliver Food to Students", WRCB TV, March 25, 2020. https://www.wrcbtv.com/story/41929241/hamilton-county-school-buses-used-to-deliver-food-to-students

[Gannon20] Gannon, J., "Feeding the hungry: A $1M assist from PNC Foundation to help fill gaps in food distribution systems", *Pittsburgh Post Gazette*, March 30, 2020. https://www.post-gazette.com/life/food/2020/03/30/COVID-19-coronavirus-PNC-Foundation-provides-meals-needy-schools/stories/202003300071

[Hobbs20] Hobbs, T.D., "Schools Rethink How to Distribute Food Due to Coronavirus", *Wall Street Journal*, April 12, 2020. https://www.wsj.com/articles/schools-rethink-how-to-distribute-meals-due-to-coronavirus-11586700000

[Kinable16] Kinable, J., W. van Hoeve, and S.F. Smith, "Optimization Models for a Real-World Snow Plow Routing Problem", *Proceedings 13th International Conference on Integration of Artificial Intelligence and Operations Research Techniques in Constraint Programming (CPAIOR 2016)*, Banff Canada, May 2016.

[Kramer07] Kramer, L.A., L. Barbulescu and S.F. Smith, "Understanding Performance Tradeoffs in Algorithms for Solving Oversubscribed Scheduling Problems", *Proceedings 22nd National Conference on Artificial Intelligence (AAAI-07)*, Vancouver Canada, July 2007.

[Laporte88] Laporte, G., Location-routing problems. In: Golden, B.L., Assad, A.A. (Eds.), Vehicle Routing: Methods and Studies. North-Holland, Amsterdam, pp. 163–198, 1988.

[Marohn20] Marohn, K., School Bus Drivers Deliver Meals Instead of Children", *National Public Radio*, Weekend Edition, March 22, 2020. https://www.npr.org/2020/03/22/819725473/school-bus-drivers-deliver-meals-instead-of-children

[Rubinstein12] Rubinstein, Z.B., S.F. Smith, and L. Barbulescu, "Incremental Management of Oversubscribed Vehicle Schedules in Dynamic Dial-A-Ride Problems", *Proceedings 26th Annual Conference of the Association for the Advancement of Artificial Intelligence (AAAI 2012),* Toronto CA, July 2012.

Appendix: Constraint Programming Problem Formulation

CP Formulation of the Penn Hills Meal Delivery Problem

Stephen F. Smith, Zachary B. Rubinstein, and Ashley Li

The Robotics Institute, Carnegie Mellon University, Pittsburgh PA 15213 USA
{sfs,zrb,ashleyli}@cs.cmu.edu

1 Current Formulation

Table 1. Variable definitions.

Variable	Definition
S	the set of delivery stops to be covered; $\|S\| = s$
V	the set of delivery vehicles; $\|V\| = v$
$Meals_k, k = 1, ..., s$	the number of meals required at delivery stop k
$TDur_{a,b},\ a, b \in S$	travel time from delivery stop a to delivery stop b
$SDur$	the fixed duration of any delivery stop
$VehicleCap_i, i = 1, ..., v$	the maximum number of meals that vehicle i can carry
$MinPerStop$	the minimum number of meals that must be delivered at a stop
est	the earliest time that delivery can start at a given stop
lft	the latest time that delivery can finish at a given stop
$iloc$	the initial location where all vehicles load the meals
$floc$	the final location where all vehicles drop off any leftover meals
$PositionMax$	the maximum time to get from iloc to the first stop of a route
$DepositionMax$	the maximum time to get from the last stop of a route to floc
$Assigned_{i,k}, i = 1, ..., s; k = 1, ..., v$	1 if vehicle i has stop k in its itinerary; Otherwise 0
$Pred_k, k = 1, ..., s$	the stop immediately before k in the route k has been assigned to
$Succ_k, k = 1, ..., s$	the next stop after k in the route k has been assigned to
$Start_k, k = 1, ..., s$	the (earliest) start time of stop k in its route
$End_k, k = 1, ..., s$	the (latest) end time of stop k in its route

Given the variables specified in Table 1, we formulate the school meal delivery vehicle assignment and routing problem as follows:

$$\max_{i,k} \left(\sum_{i=1}^{v}\sum_{k=1}^{s} Assigned_{i,k} \times Meals_k\right)$$

Subject to:

$$\forall i \in V \left(\sum_{k=1}^{s} Assigned_{i,k} \times Meals_k \leq VehicleCap_i\right) \tag{1}$$

$$\forall k \in S\ (\sum_{i=1}^{v} Assigned_{i,k} \leq 1) \tag{2}$$

$$\forall i \in V\ (\sum_{j=1}^{s-1} \sum_{k=j}^{s} Assigned_{i,j} \times Assigned_{i,k} \Rightarrow (End_j < Start_k \vee End_k < Start_j) \tag{3}$$

$$\forall i \in V\ (\sum_{k=1}^{s} Assigned_{i,k} \times (SDur + \sum_{k=1}^{s} Assigned_{i,Succ_k} \times TDur_{k,Succ_k})) \leq (lft - est) \tag{4}$$

$$\forall i \in V\ (\exists k \in S \mid Assigned_{i,k} \wedge \neg Pred_k \wedge (TDur_{iloc,k} \leq PositionMax) \tag{5}$$

$$\forall i \in V\ (\exists k \in S \mid Assigned_{i,k} \wedge \neg Succ_k \wedge (TDur_{k,floc} \leq DepositionMax) \tag{6}$$

$$\forall k \in S\ (\sum_{i=1}^{v} Assigned_{i,k} = 1) \Rightarrow (Start_k \geq est) \tag{7}$$

$$\forall k \in S\ (\sum_{i=1}^{v} Assigned_{i,k} = 1) \Rightarrow (End_k \leq lft) \tag{8}$$

$$\forall k \in S, \forall i \in V\ (Assigned_{i,k} = 1)\ \Rightarrow\ (Meals_k \geq MinPerStop) \tag{9}$$

Constraint (1) ensures that the number of meals required for each vehicle route does not exceed the vehicle's carrying capacity. Constraint (2) specifies that a given stop belongs to at most one route. Constraint (3) specifies that the stops of a given vehicle route are totally ordered, and constraint (4) ensures that there is enough time to execute each route within the specified delivery window. Constraints (5) and (6) enforce maximum travel times from the food pantry to the first stop and from the last stop to the extra food drop off location. Constraints (7) and (8) make sure that all stops that have been assigned have scheduled start and end times that actually fall within the delivery window. Constraint (9) specifies that a minimum number of students must be serviced at each stop.