Bus Routing Optimization Helps Boston Public Schools Design Better Policies

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Abstract. In the winter of 2016, Boston Public Schools (BPS) launched a crowdsourcing national competition to create a better way to construct bus routes to improve efficiency, deepen the ability to model policy changes, and realign school start times. The winning team came from the Massachusetts Institute of Technology (MIT). The team developed an algorithm to construct school bus routes by assigning students to stops, combining stops into routes, and optimally assigning vehicles to routes. BPS has used this algorithm for two years running; in the summer of 2017, its use led to a 7% reduction in the BPS bus fleet. Bus routing optimization also gives BPS the unprecedented ability to understand the financial impact of new policies that affect transportation. In particular, the MIT research team developed a new mathematical model to select start times for all schools in the district in a way that considers transportation. Using this methodology, BPS proposed a solution that would have saved an additional $12 million annually and also shifted students to more developmentally appropriate school start times (e.g., by reducing the number of high school students starting before 8:00 a.m. from 74% to 6% and the average number of elementary school students dismissed after 4:00 p.m. from 33% to 15%). However, 85% of the schools’ start times would have been changed, with a median change of one hour. This magnitude of change led to strong vocal opposition from some school communities that would have been affected negatively; therefore, BPS did not implement the plan.

Introduction

With over 54,000 students across 125 schools in the 2018–2019 school year, Boston Public Schools (BPS) is the largest school district in Massachusetts and New England and the 76th largest school district in the United States. Founded in 1647, it is also the oldest school district in the United States and home to the nation’s first public school, Boston Latin School, which opened in 1635. Today, the district serves predominately Hispanic (42%) and black (34%) students and some white (14%) and Asian (9%) students. Two of every three BPS students receive some form of state aid, one of three is an English learner, and one of five has a disability. Since 1993, the district has operated as the largest individual department within the City of Boston overseen by a seven-member school committee appointed by the mayor, with a budget of $1.3 billion in 2017 (Boston Public Schools 2018).

History

Like most U.S. school districts, BPS is responsible for providing transportation to and from school for many of its students. The era of significant busing in Boston began in 1974, when Federal District Court Judge W. Arthur Garrity ruled that the Boston school committee was intentionally and unconstitutionally segregating black and white students. In Morgan v. Hennigan (1974), Judge Garrity ordered the district to begin busing 18,000 Boston students out of their segregated neighborhoods to different schools across the city. Judge Garrity’s decision was highly contentious, and in the first five years of busing, 30,000
predominantly white students moved out of Boston to attend suburban schools or left the district to attend parochial schools. Although court-ordered desegregation ended in 1988, racial integration continues to be an issue within Boston: some have argued that today Boston’s schools are even more segregated than in the past (Maffai 2016, Braude 2018).

Beyond segregation, many historically marginalized students do not have an excellent school near their homes today. BPS is committed to providing access to quality schools for all students. One way that BPS does this is through a pioneering and progressive school choice program (Abdulkadiroglu et al. 2005, Pathak and Shi 2013). This progressive choice program has led to high costs; giving families greater latitude in choosing the school that is right for them has led to complex citywide enrollment patterns, with students often attending schools far from their homes (see Figure 1). Compared with other districts in Massachusetts and urban districts across the country, a relatively high proportion of BPS students are eligible for transportation. Because these schools draw students from across the city, their sparse yet spread-out enrollment distribution—coupled with a one-hour ride time maximum—results in challenges to creating full and efficient routes.

In addition to these equity-minded policies, BPS faces a structural obstacle in designing bus routes: the city’s meandering topography. Many roads in Boston sprung up from footpaths (or cow paths, as legend has it) around the shoreline and the banks of the Charles River, and the city was built without cars in mind. With one-way streets, dead ends, and winding roads, the map of Boston looks nothing like the uniform grid

**Figure 1.** (Color online) Enrollment at a Typical Public School in Boston Is Dispersed Across the City

Note. Although most students (circles) live relatively close to the school (square), the rest are scattered across the city.
of such cities as New York, Denver, and Chicago, a fact epitomized by Washington Street intersecting School Street five unique times.

**BPS Transportation**

In 2017, BPS provided school bus transportation to 25,000 students. This includes not only BPS students but also, because of state requirements, some Boston students attending local charter, private, and Catholic schools. Among the 25,000 transported students, about 5,000 students have special needs: because of their disabilities, they cannot safely or reliably navigate to a standard corner bus stop and therefore require door-to-door service; that is, pickup at home. A bus picking up any of the 25,000 students will drop off the students at their schools; like many U.S. school districts, BPS does not use a hub-and-spoke model in which students are required to transfer from one public school bus to another. Although a team of expert routers within BPS creates the routes, a third-party contracting company operates the fleet of over 700 BPS-owned buses. The diverse needs of the transported students mean that the routing problem has many additional constraints. For example, the BPS bus fleet is highly heterogeneous: buses differ in the number of seats (e.g., 71-seat full buses, 30-seat half buses, and 15-seat minibuses) as well as in the availability of wheelchair spots (some half buses convert seat space to wheelchair docks), child safety restraints (i.e., special seat belts), and even air conditioning. In addition to creating routes for the year, BPS’s transportation officers also ensure that buses carry an appropriate number of adult monitors to ensure child safety and update routes throughout the year as students change addresses, enroll at different schools, and opt in or out of transportation services.

In 2017, BPS spent $120 million (~10% of its total budget) on transportation, by far the highest per-student transportation cost in the nation. Moreover, between 2010 and 2017, the cost of transportation grew by 5%–7% a year, much faster than the overall revenue growth of the district (2%–4%). In Boston, most transportation costs are driven by the total number of buses operating each day—an estimated cost of roughly $100,000 per bus per year.

To reduce the number of buses needed, Boston, like many other school districts, staggers school start times (often called bell times in reference to the bell indicating the start of school). Generally, BPS schools start at one of three bell tiers—7:30, 8:30, or 9:30 in the morning. This allows each school bus to serve several schools in succession in both the morning and afternoon; however, it makes the system more interconnected and therefore more complex.

**The Need for Analytics**

In the fall of 2015, BPS began to develop a long-term financial plan to spark a public conversation about BPS’s overall spending. The report concluded with “10 Big Ideas” to help the district spend more strategically to improve student outcomes and close the district’s structural deficit. Many of these ideas included complex and challenging policy questions, such as changing tenure law, realigning state funding laws, and closing schools.

Four of 10 proposed ideas explicitly involved transportation. The first two proposals relied on changing student bus assignment policies. For example, BPS provided more generous transportation eligibility than required by state law: students living more than a mile away from school were eligible for a public school bus compared with state law, which specifies that only students living more than two miles away are eligible. One proposal called for making the school bus routing more efficient. Another involved reevaluating school day lengths at different schools. The report also pointed out that “[if] BPS were able to better balance school start times, then buses could be used more efficiently, thereby reducing the number of buses needed” (Boston Public Schools 2016, p. 27). These policy changes impact a wide range of stakeholders, including students, staff, teachers, and families, in many different ways, both academic and nonacademic.

To understand the impact of new policies and thus make informed decisions about them, it is crucial for BPS, like any school district or government body, to accurately estimate their financial impact. However, in 2017, BPS—like every other school district with a sizable transportation budget—did not have the technological capacity to perform this kind of analysis. Although BPS has used commercial software to manage student assignments to buses and routes for several years, the system does not have the capability to route automatically and accurately. Instead, the district relied on its team of 10 full-time transportation officers to manually draft 45,000 miles of routes for 650 buses. It took this team about 3,000 total people-hours to create a schedule for the entire fleet. Given the substantial time commitment necessary to create and maintain routes for its 25,000 transported students, the BPS transportation team could not realistically be tasked with creating different routing solutions to determine the cost of every proposed new policy.

**School Start Time**

Because BPS staggers the start and end times of different schools, the system of bus routes is so interconnected that small tweaks often have significant
transportation implications. For example, in 2016, a change to one school’s start time caused an unexpected cost increase of more than $1 million.

BPS is far from alone in confronting the challenge of adjusting school start times. Indeed, the issue of choosing appropriate school start and end times has received increased attention in recent years. A growing number of studies have linked too early school start times to a wide array of teen health issues, including obesity (Chen et al. 2008), depression (Fredriksen et al. 2004), and traffic accidents (Danner and Phillips 2008). Curcio et al. (2006) and Owens et al. (2010) found that starting school too early can reduce teenage cognitive abilities, which can, in turn, reduce academic achievement (Carrell et al. 2011).

Crowley et al. (2007) argue that changes in the body’s circadian clock during puberty effectively prevent adolescents from getting adequate sleep early in the night. Although the American Academy of Pediatrics recommends a start time no earlier than 8:30 a.m. for teenagers, a recent Centers for Disease Control and Prevention (CDC) report by Wheaton et al. (2015) found that only 17.7% of U.S. high schools comply. Hafner et al. (2017) estimate that over the next 10 years, the dire public health implications of early start times by high schools could impact the U.S. economy by over $80 billion.

Moreover, research by Edwards (2012) suggests that these repercussions disproportionately affect the most economically disadvantaged students. Because achievement gaps among students from different backgrounds remain stark (Wiggan 2007), research, including the work of Cohen et al. (2006), has consistently found systematic biases, largely along racial lines, that partially explain these gaps.

**An Analytics Challenge**

In 2016, BPS set out to find a provider or service that could sufficiently automate school bus routing and determine the cost of these scenarios. Conversations with a number of vendors, including those of leading routing or mapping platforms, revealed that a ready-made solution was not yet available. Boston’s routing problem, with many additional constraints on top of an already difficult decision problem, was seemingly too complex.

Therefore, BPS decided on a 21st-century solution: crowdsourcing. More precisely, it organized a two-part, 60-day “hackathon,” inviting teams from industry and academia to solve its problem. Participating teams signed a nondisclosure agreement and received appropriately anonymized data, including approximate student home addresses, school locations, and a list of previously vetted corner bus stop locations. In the first 30 days, the teams needed to produce a full routing solution, including assigning each student to a bus stop, connecting stops into bus trips, and connecting trips for different schools into a bus itinerary in both the morning and afternoon. In the last 30 days, they needed to integrate their routing engine into a tool to select and evaluate school start time proposals.

The BPS transportation challenge represented a radical new way to conduct government business. Although local governments are starting to leverage the recent popularity of hackathons in the software and analytics community, this was a problem that could not be solved in a sleepless weekend; indeed, the Massachusetts Institute of Technology (MIT) team estimated that it spent over 800 people-hours on the first round of the challenge. The innovative nature of the challenge allowed BPS to interest and bring on board major sponsors, including Microsoft, Google Maps, and private donors who pledged $15,000 in prize money for each of the two rounds (i.e., routing and bell times). Furthermore, the problem that BPS posed was intriguing, especially from an operations research (OR) standpoint: a vehicle routing problem, by some measures one of the oldest OR problems (originally proposed by Dantzig and Ramser 1959), with the new requirement of start time assignment.

The challenge attracted many participants from across the country. The innovative challenge format allowed BPS to directly compare results from participating teams rather than the usual proposals from vendors. In the end, the submission from the MIT Operations Research Center won the competition, initiating the collaboration between BPS and MIT that we describe in this work.

**School Bus Routing**

The problem of school bus routing has been studied extensively in the OR literature as an interesting special case of the vehicle routing problem (Desrosiers et al. 1995, Park and Kim 2010). It is typically decomposed into three main subproblems, as we illustrate in Figure 2, (d)–(f).

- **Stop assignment.** Choosing locations (typically street corners that have been vetted for safety) to which students will walk from their homes to be picked up.
- **Bus routing.** Linking those corner and door-to-door stops together into bus trips.
- **Bus scheduling.** Combining bus trips into a route that can be served by a single bus.

Optimization-based algorithms exist for these subproblems in isolation: for example, Schittekat et al. (2006) propose a mixed-integer optimization to stop assignment and bus routing, whereas Fügenschuh (2009) develops a network flow approach to bus scheduling.

However, the literature on optimally combining subproblem solutions, particularly for bus routing
and scheduling, is less extensive. Approaches typically involve formulating the school bus routing problem as a large combinatorial optimization problem, which can be solved using metaheuristics, including local search (Spada et al. 2005), simulated annealing (Chen et al. 2015), and special-purpose-vehicle routing heuristics (Bramel and Simchi-Levi 1995, Braca et al. 1997).

One of the major hurdles between theory and implementation in school bus routing is that the routing problems faced by different districts can dramatically vary because of different rules and policies, priorities, or environments (e.g., urban versus rural). Much of the school bus routing literature focuses on special-purpose algorithms that address variants of the school bus routing problem. For example, Braca et al. (1997), Spada et al. (2005), and Park et al. (2012) allow mixed loads (i.e., students from different schools riding together on the bus), and Bögl et al. (2015) study the possibility of including bus transfers. Additionally, some works (Spada et al. 2005, Fügenschuh 2009, Park et al. 2012, Chen et al. 2015) consider the problem using arrival time windows at each school instead of a single arrival time.

Because solving a school bus routing problem has immediate and potentially considerable impact in practice, researchers have focused more on finding feasible solutions than on proving theoretical bounds on their optimality. However, in recent years, some authors, such as Zeng et al. (2017), have approached school bus routing subproblems from new theoretical and modeling angles with the objective of finding both stronger guarantees and better feasible solutions.

The exact setting of the school bus routing problem varies significantly from country to country and even from district to district. The new framework for school bus routing proposed here was developed with BPS’s routing problem in mind; however, its central idea, called biobjective routing decomposition (BiRD), generalizes to many other settings. It allows the method to leverage the best available routing methodologies and combine their results in a synergistic way.

The BiRD algorithm consists of several steps (Figure 3) for which the MIT team developed optimization-based approaches, which it implemented using modern software tools, including Julia (Bezanson et al. 2017) and JuMP (Dunning et al. 2017), and available online tools (Delarue and Martin 2018). For clarity, we focus on the morning problem, but the algorithm generalizes to the afternoon. Because problem details often vary between districts, adjusting some steps to changes in the problem setting may be advantageous. BiRD’s defining feature is thus the decomposition of the problem and particularly the scenario selection step, which bridges the gap between the single- and multiple-school subproblems. We provide an overview of the methods here; Bertsimas et al. (2019) include full details.

Figure 2. (Color online) The School Bus Routing Problem Can Be Decomposed into Several Subproblems

Source. Bertsimas et al. (2019).
Notes. (a) This representation of BPS 2017–2018 data (anonymized) shows students as triangles and schools as pentagons. (b) A sample BPS routing solution, with schools as pentagons, bus stops as squares, and lines connecting bus stops that are served in sequence by the same bus, illustrates the complexity of Boston school transportation. (c) In this small synthetic district (three schools), students (triangles) are the same color as their assigned schools (pentagons). Panels (d)–(f) illustrate three main routing steps in this district: stop assignment (d), where students (triangles) attending a school (pentagon) are shown connected to their assigned stops (squares); one-school routing (e), where all bus stops for the orange school are connected into bus trips; and bus scheduling between multiple schools (f), where three trips (one from each school) are connected into a single bus itinerary.
Single-School Routing
To assign students to stops (Figure 2(d)), the approach uses an integer optimization formulation of the assignment problem, with maximum walking distance constraints. We minimize the overall number of stops for two reasons: (1) it simplifies bus trips, and (2) it takes time for a bus to come to a complete stop and open its doors, which means that the minimum pickup time at a stop is typically high, even if the stop has few students. When long bus routes span the entire city, as in Boston (Figure 2(b)), stop assignment has a negligible effect on the macroscopic quality of the routing solution.

The approach then includes an insertion-based algorithm to connect sequences of stops into feasible bus trips (Figure 2(e)). Integer optimization is used to combine these feasible trips with a minimum number of buses, with a set cover formulation inspired by crew-scheduling problems (Smith and Wren 1988). Because route generation and route selection are separated, the algorithm can tractably handle practical modifications in the routing problem from vehicles with different capacities to student and bus compatibility restrictions (e.g., students in a wheelchair need a bus with a special ramp or lift).

Multiple-School Routing
To solve a large-scale school bus routing problem, the algorithm uses the single-school routing method to generate not one but several varied optimized routing scenarios for each school to select the best one for the system. In particular, it considers several scenarios on the Pareto frontier of two objectives (hence the name biobjective routing decomposition), number of buses, and average riding time. This trade-off is motivated by the fact that shorter routes are more easily connected into bus schedules.

Then the algorithm first jointly selects one scenario for each school in a way that favors maximal reuse of buses from school to school (Figure 3) by formulating an integer optimization problem with a network flow structure that seeks to minimize the number of buses at the scale of the entire district. Given one routing scenario for each school, solving another integer optimization problem identifies a trip-by-trip itinerary for each bus in the fleet (Figure 2(f)). In this final subproblem, we optimize the number of buses jointly in the morning and the afternoon.

Implementation
We completed our testing of the BiRD algorithm on the anonymized challenge data in early June 2017. Results showed that the method could yield a reduction in the bus fleet of up to 20%, which would represent significant savings for BPS, with little to no reduction in the quality of service (i.e., time spent on a bus and distance walked to a stop). Given the success of the challenge, BPS decided to take another bold step and use BiRD to route buses for the upcoming school year, which would start in just under three months.
Over the next few months, the BPS and MIT teams were in contact at all hours every day in working to prepare the files for the summer. The MIT team worked on adapting the algorithm to handle additional secondary constraints that had not been part of the original challenge but were vital for safe and sensible routing. For example, the number of students that can fit on a bus varies by the grade of a student; a large bus can comfortably seat 71 kindergartners but far fewer high school students. Moreover, to address the challenge, the MIT team used Google Maps data, which typically provide travel time estimates for cars, not buses. As a result, in the challenge solution, some large buses were routed on narrow or low-clearance roads. The modular nature of the BiRD algorithm was central to adapting to these constraints.

While the MIT team was working on building a routing solution and an interface for the BPS staff to use when copying routes into BPS’s existing route management software, the BPS team was working to gather information to confirm enrollment for the upcoming year. Because of high levels of student mobility and because BPS serves a variety of school types, including traditional district schools (BPS), publicly funded charter schools, private schools, and Catholic schools, gathering an accurate enrollment file is not an easy task. In previous years, the delay in obtaining enrollment data had been less of an issue because transportation officers simply started with schools with full enrollment information while waiting for the rest of the data to arrive. We designed the new school bus routing algorithm precisely to improve on the piecemeal nature of the manual approach. As a result, obtaining accurate enrollment earlier in the process became significantly more important.

We completed a final solution and routing interface in mid-July. Over the next month, BPS convened a team to manually upload the 2,800-trip solution, one trip at a time, into the BPS route management software. The software turned the routes into specific turn-by-turn directions and bus rosters for drivers and provided continuity in route management over the course of the school year. Then BPS’s team of transportation officers—seasoned routing experts who build and update the routing solution every year as enrollment patterns change—made manual tweaks and took ownership of the solution.

The algorithmic solution had a number of advantages over the previous manual solution. Foremost, it resulted in an immediate fleet reduction of 75 buses (12% of the fleet). Although this was less than the initial promised reduction of 20%, it reflected BPS’s abundance of caution on a number of issues. For example, BPS was nervous that road speed estimates might prove to be overly optimistic or that start-of-the-year enrollment changes, which often surpass several hundred a day for the first few weeks, would cause an overly optimized system to break. After the school year started, BPS would be largely unable to change the bus stops to which students were assigned without causing significant disruption in the lives of these students. Throughout the routing process, we planned for BPS staff to “add back” buses, providing additional flexibility to the solution.

After these tweaks, BPS sent a proposed system of routes to its external fleet operator. BPS had reduced the fleet by 7% (50 buses). An OR method that did not exist in March 2017 had been successfully implemented just five months later, allowing BPS to save an estimated $5 million in transportation costs; in addition, it eliminated 20,000 pounds of carbon emissions every day. This was the largest fleet reduction in the history of the district—even larger savings than had been realized a few years earlier by moving all seventh and eighth graders from public school bus service to standard public transportation provided by the Massachusetts Bay Transportation Authority (MBTA). The solution was not perfect; however, given the time frame involved, it was undeniably a major success.

Although the solution was thoroughly verified by the BPS transportation team, the ultimate test of the new solution came on the first day of school. Would the algorithmically constructed routes hold up in practice? Would students get to school and arrive on time? Early performance was not encouraging, with buses’ on-time performance in the first week significantly lower than in the first week of the previous year. A number of factors contributed to this difficult start: unavoidable human errors in uploading and adjusting the routes, discrepancies between car travel times (used by the algorithm) and bus travel times, and a noticeable drop in the average school bus driving speed. However, after an initial adjustment period, the on-time performance improved steadily; by November, it surpassed the previous year’s week-to-week on-time performance and remained close to past on-time performance throughout the year. Throughout the year, the transportation officers were instrumental in improving on-time performance as they worked to fix routes and handle enrollment changes.

**Operations Research for Public Policy: Setting School Start Times**

In the first 30 days of the transportation challenge (the routing-focused portion), BPS saw the opportunity for participants to explore a small policy change. For several years, the maximum distance that students could walk to the bus stop was half a mile for all students (although students actually walked less than half of that, 0.2 mile, on average). In the transportation
challenge, BPS introduced a new equity-minded and student-specific distance constraint, which took into account both the grade of the student and the safety of the neighborhood (thereby imposing a constraint that younger students or students in less safe neighborhoods would walk a shorter distance).

The modularity of BiRD allowed it to easily consider this new constraint. Results suggested that the effect of this policy on cost was negligible. Although seemingly innocuous, this result represented the first time that BPS created a complete potential bus schedule to calculate the transportation impact of a proposed policy change. Being able to properly examine the transportation impact of these changes when still at the proposal stage is of enormous benefit to BPS (or any other school district), and it is impossible without the ability to rapidly route within the entire system.

Formulating the Start Time Selection Problem

The ability to evaluate new policy ideas encouraged BPS to explore tackling one of the most complex policy changes on its list of big ideas: school start and end times. From a technical perspective, this is an exciting OR problem, which has not been studied extensively in the literature. A few school bus routing methods, such as Fügenschuh et al. (2005) and Fügenschuh and Martin (2006), identify adjusting school start times as a way to reduce bus routing costs. However, as Malone et al. (2017) point out, the problem of school start times involves not only school transportation but also complex health and policy issues. School time selection is not simply an extension of school bus routing but a policy problem that cannot be solved in practice without the ability to accurately model the transportation implications. For example, there has long been a push within BPS to move bell times to more developmentally appropriate times; however, the difficulty in accurately modeling transportation costs and the significant cost risks from implementing the wrong set of times have made the district nervous to make these changes blindly. The recent work of Banerjee and Smilowitz (2018) shares this perspective on school time selection.

Selecting bell times is a complex policy problem with many stakeholders. We first focus on the interplay with transportation because computing school bus routes is a necessary component of bell time selection. For example, it is of interest to evaluate transportation costs when each school is assigned a particular bell time. However, because the number of possible assignments grows exponentially with the number of schools, a simple enumerative approach is not tractable. Instead, we develop a general formulation for the school time selection problem (STSP), which includes a tractable proxy for transportation costs constructed using BiRD. We will then show how to include other community objectives.

Transportation Costs

A key factor in an optimized school bus routing solution is the “compatibility” of pairs of trips: that is, how easy it is for a single bus to serve them with minimum idle time in between. The school time selection method defines a trip compatibility cost that trades off (1) the feasibility of a bus serving the two trips sequentially and (2) the amount of idle or empty driving time involved, with trade-off parameters that depend on characteristics of the school district and can be found using crossvalidation. Then, for any pair of schools, a routing pairwise affinity cost is defined, which is the sum of the compatibility costs between every trip in every routing scenario for these two schools.

Because the objective function includes only pairwise affinity costs, the presented model of the STSP is a special case of the generalized quadratic assignment problem (GQAP), which Hahn et al. (2008) describe. When different GQAP formulations for the STSP were investigated in Wenzel (2016), even small instances could be intractable, but a simple local improvement heuristic turned out to work quite well in practice. Given initial bell times, a random subset of schools is selected. The problem of finding the optimal start times for this subset while fixing the start times of all other schools is a smaller GQAP, which can be solved in seconds using mixed-integer optimization. The operation is repeated with new random subsets until convergence. Results on synthetic data in Bertsimas et al. (2019) suggest that a subset size of one gives near-optimal results if the local improvement heuristic is run several times with random starting points.

In Boston, as in many other districts, schools usually start at one of three times (7:30, 8:30, or 9:30 in the morning), allowing each bus to serve up to three schools every morning (Owens et al. 2014). To leverage the transportation efficiencies from staggered start times, most districts, including Boston, try to balance the number of bus trips across all three time tiers. Bertsimas et al. (2019) showed that distributing schools across tiers without accounting for geography or routing compatibility can lead to significant inefficiencies. In addition, in a city like Boston, the dispersion of students means that accounting for routing compatibility is beyond the reach of simple heuristics and requires more advanced modeling.

Another advantage of the school time selection model is that it is not necessarily limited to only three feasible start times. BPS leveraged this ability to explore 10 possible start times for each school (every 15 minutes between 7:15 a.m. and 9:30 a.m.). In Boston, when optimizing purely for transportation cost, we
can find a set of bell times that requires the use of only 450 buses by the district (compared with 600 currently). Of course, selecting school start times is not simply a transportation exercise; it is a multifaceted policy problem. Thus, the real advantage of our STSP formulation is the multiobjective component, which we present next.

School Start Times in Boston

As we discussed earlier, public schools currently start at one of three start times. These three times are not equally desirable: 8:30 a.m. is typically preferable to 7:30 a.m. and 9:30 a.m.; in the interest of fairness, Boston’s last start time policy, enacted in 1990, stipulates that after five years, schools with 7:30 a.m. start times must move to an 8:30 a.m. start, 8:30 a.m. schools must move to 9:30 a.m. starts, and 9:30 a.m. schools must move to 7:30 a.m. starts. However, over the past 15 years, the difficulties of implementing change every 5 years meant that the policy has not been enforced. These times affect only BPS schools—BPS is not able to set or change the times of non-BPS private, Catholic, or charter schools. Staggering school start times has undeniably allowed BPS to invest significant sums of money into classrooms instead of school buses. However, as enrollment patterns have changed, the number of routes at each of these tiers is no longer split evenly, suggesting that these bell times are not as efficient as they could be from a transportation standpoint.

In addition, over 74% of Boston high school students currently start school before 8:00 in the morning. As we mention earlier, the negative effects of early high school starts are magnified in economically fragile students. However, in Boston, such students have worse bell times, on average, than economically advantaged students (Shuster 2017). For example, in Figure 4, we see that economically disadvantaged high school students are more likely to start before 7:30 a.m. than other high school students.

Beyond Transportation

BPS start times have not undergone system-wide change for decades, despite these shortcomings. Changing bell times is intrinsically difficult because stakeholders cannot agree on what is best for everyone. Figure 5, (b) and (c), shows community preferences for different start times across all public schools based on a BPS survey; Bertsimas et al. (2019) provide more details. Although families and school staff tend to favor start times between 8:00 a.m. and 8:30 a.m., the displayed preferences are mostly characterized by broad disagreement, even within a single school (Figure 5(c)). Any bell time for any school is certain to have both fervent supporters and vehement critics.

Based on these data, in setting the bell times for only one school, let alone a system of schools, school districts cannot satisfy all, or even most, of their constituents. Still, some scenarios are more popular than others. As Figure 5(a) shows, trying to satisfy the individual preferences of parents and staff can be prohibitively expensive. Each additional point of community satisfaction in Boston costs dozens of additional buses and tens of millions of taxpayer dollars.

For BPS, the trade-off curve in Figure 5(a) represented a significant step forward in that it was the first time that any district could visualize, or even quantify, any trade-offs of bell time policymaking. The curve illustrates the model’s ability to provide a district with the quantitative support necessary to understand the problem and make the best decision. Although stakeholders have many competing personal priorities, they often agree on broader goals, such as having fair and equitable bell times or reinvesting transportation savings into schools. Starting in 2016, BPS led a public engagement process to understand this problem and make the best decision.
these broad values. Four main themes emerged: maximizing the number of high school students who start after 8:00 a.m., minimizing the number of elementary school students who end after 4:00 p.m., prioritizing schools with high special education needs, and reinvesting transportation savings into classrooms. Of course, BPS aimed to achieve these objectives in a manner that ensured balanced times across various racial and socioeconomic groups and neighborhoods.

In the general case, solving the STSP in practice means optimizing a set of several objectives, such as the ones that we outlined earlier. An objective is called GQAP representable if it can be represented using only single-afiinity costs (representing the aversion of a particular school to a particular bell time) and pairwise affinity costs. The GQAP framework developed earlier was found to have sufficient modeling power to represent all the objectives and constraints that interest school districts in general (Bertsimas et al. 2019) and Boston in particular. Typically, school districts wish to balance multiple GQAP-representable objectives, including transportation costs. As is usual in multiobjective optimization, the final cost function to optimize is a weighted average of the district’s different (i.e., GQAP representable) objectives, with weights indicating policymakers’ priorities.

Using this methodology, BPS explored tens of thousands of trade-offs, such as those presented in Figure 6. The flexibility of the methodology allowed BPS to take into account a number of specific constraints (e.g., preventing large neighboring high schools from dismissing at the same time, which could create unsafe situations at neighboring MBTA stops). In the end, the proposed bell times (see Figure 6) were projected to reduce the number of high school students starting before 8:00 a.m. from 74% to 6% and the number of elementary school students dismissed after 4:00 p.m. from 33% to 15%. The plan also projected an estimated reinvestment of $12 million into classrooms.

**Dramatic Change Prevented Implementation**

The high-level objectives presented to the school committee were generally received with broad agreement...
in Boston because of extensive community engagement leading up to the formulation of these objectives and the understanding that several of them aligned with research on adolescent sleep patterns and district-wide goals (e.g., later high school start times and savings in transportation that could be reinvested in classrooms). The solution proposed by BPS matched these objectives at a high level. However, after the bell times of individual schools were revealed, a different picture emerged. Achieving these results required a significant amount of change: over 85% of schools were projected to change their start times, with a median change of one hour. Some school start times changed by over two hours. Many families expressed concern that they would not be able to rearrange their schedules to accommodate a change of this magnitude.

This concern had not been captured in the BPS community survey, which asked families to evaluate different bell times but did not explicitly put those bell times in context with each school’s current bell time. In addition, the survey focused mostly on start times. Of course, a start time and a fixed length of day fully specify an end time, but start times were not explicitly mapped to end times, thus potentially affecting the survey responses of many families. Kalton and Schuman (1982) show that the way that a question is worded or framed can introduce biases into responses; therefore, it is possible that some families’ aversion to certain times was underestimated. Another major issue raised by parents was before- and after-school programming. Although BPS planned to reinvest savings from transportation into expanding before- and after-school supports for students, these plans were general rather than school specific. Because of this, parents were not sure of which before- or after-school supports, if any, their school would provide during the coming year.

In addition, as we discussed earlier, general disagreement at each school means that any new bell time at any school is guaranteed to have some detractors. A well-known result from Tversky and Kahneman (1974) is that individuals often exhibit loss-aversion behaviors; that is, they prefer avoiding losses to acquiring gains of the same magnitude. In Boston, it seems that people who felt that their bell times would become worse were more vocal than people who felt that their bell times would improve. Recall also that current bell times in Boston do not meet the district’s standards for equity because elementary students in wealthier neighborhoods start later (see Figure 4). Because the proposed bell times were more equitable than the status quo, those who had the most to lose were those who were most advantaged by the status quo.

Finally, probably the most compelling argument voiced by concerned families involved community engagement. Many parents who were happy with their current start and end times did not participate in the process, assuming that their times might not change. Despite BPS efforts, they were not able to draw out a representative sample of families in their engagement process. In addition, many who did engage in the community engagement process felt that there was a disconnect between the means used to communicate and gather information (e.g., the survey, townhalls, focus groups, and messages sent home) and the magnitude and immediacy of the change. In particular, many families did not feel that their voices had been heard. Although the BPS community survey included both online and telephone versions to reach families without internet access, was translated into several languages for families who do not speak English at home, and had a comparatively high response rate, there is evidence (e.g., in Figure 4(c)) that the BPS community survey was not fully representative of the district’s opinions. Many families did not feel prepared for such a significant and system-wide change.

Ultimately, the district decided that such an important decision should not be implemented without deeper community engagement, and the new bell times did not become a reality. However, the effort showed the potential for using an algorithm to solve a seemingly intractable public policy dilemma.

Conclusions
A National Conversation

Since the MIT team developed these new OR tools, it has contributed to a growing national conversation about school start times. In September 2018, the MIT team provided data for the Boston Globe’s top-trending interactive article, “The Equity Machine” (Scharfenberg 2018), which allowed readers to visualize the policy trade-offs of different bell time scenarios. School start times are a complex policy issue, and communicating with the public about the trade-offs involved is a critical step in designing any good solution.

In solving a problem widely considered impossible, the MIT team has helped OR to surge to the front of the national debate about school start times. Although bell times in Boston have not changed, the Boston school committee approved a new policy that explicitly outlines quantifiable objectives that future bell time assignments should seek to optimize (Sullivan 2017). Buoyed by media coverage, including the Wall Street Journal, NPR, and the Boston Globe, the MIT team has been solicited by dozens of policymakers at the state and local levels and notably testified before the Rhode Island House of Representatives in March 2018.

From Boston to the World

In Boston, the increased efficiencies resulting from optimized school bus routing remain, and work continues
to ensure that BPS school bus routes are designed so that students arrive at school safely and on time in the most cost-efficient way possible. The need for a principled OR approach to the logistics and policy problems faced by school districts across the country has led to the development of a new software system for school transportation and policy by Dynamic Ideas, a company started by Dimitris Bertsimas. Dynamic Ideas is currently in talks with almost 30 districts (and is directly partnering with 3 districts) across 17 states to implement routing and/or bell time solutions. In an increasingly interconnected world, it is our firm belief that OR has a critical role to play in helping policymakers understand the implications of new proposals so that they can make informed decisions.

Acknowledgments

The authors thank Andres Weintraub for helpful feedback at the Edelman competition semifinalist stage; the 2019 Edelman committee for selecting our work as a finalist; and Harrison Schramm and Sudharshana Apte for providing many helpful comments, suggestions, and answers as coaches. They also thank Dick den Hertog for his careful reading of our manuscript as well as Vivek Farias, Jonas Jonasson, and Nikos Trichakis for reading earlier versions. This work benefited greatly from conversations with Cindy Barmhart, Kade Crockford, Saurabh Datar, Joi Ito, Jo Craven McGinty, Georgia Perakis, David Scharfenberg, and Irfan Uraizee. The authors particularly thank all members of the BPS working group on start times for sharing their viewpoints and experience. They are grateful for the work put in by the BPS leadership and transportation teams, and in particular, they thank the transportation officers for their dedicated work to ensure that every BPS student can get to school in the morning. Finally, the views expressed in this paper are the views of the authors and do not reflect the official position of Boston Public Schools or the City of Boston.

References


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