

Converting a Large Region to a Multimodal Pulsed-Hub Public Transport Network

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Applicability of the cost-effective strategy used in Switzerland that successfully integrates all public transport for the entire country into a multi-hub timed-transfer system (pulsed-hub network) is investigated using the greater San Francisco Bay Area as an illustrative case study. For the existing and proposed Bay Area rail service routes, the study investigates the optimal repeating (clock-face) base headway for the pulsed-hub network, hub spacing, and locations (ideally adjacent to dense and diverse land uses providing destinations within walking distance, preferably a downtown), and hub station design to minimize transfer walk times. A pulsed-hub network schedule, because of the repeating schedule, can be shown as a schedule map that represents typically a 1-h schedule module. The schedule map, showing the routing and travel times between hubs and the pulse timings by means of a clock face at each hub, becomes a tool to develop the multihub system and to communicate with all stakeholders, including policy makers and the public. The illustrative pulsed-hub network uses existing and proposed rail services and express buses on high-occupancy vehicle lanes. These include the two publicly owned regional rail systems, Bay Area Rapid Transit and the Peninsula Commute Service (Caltrain); the intercity Amtrak-operated Capitol Corridor trains between San Jose, Oakland, and Sacramento (assuming that reliable passenger service can be maintained by freight railway by providing schedule windows for both passenger and freight trains); the proposed Sonoma-Marina Area Rail Transit and Dumbarton Rail Bridge routes; and the proposed California high-speed trains, currently in environmental review.

Other authors in previous work have developed and analyzed comprehensive timed-transfer systems for urban areas under the jurisdiction of a single public transit agency (1, 2). (In a timed transfer, transit vehicles such as buses or trains are scheduled to stop near each other to allow passengers to transfer between the vehicles via a short walk.) This paper investigates, in an illustrative fashion, the establishment of a comprehensive timed-transfer system for a large multicentered urban region with multiple public transportation agencies that requires capital investment.

The region selected for the illustrative case study is the central California region centered on the San Francisco Bay Area and extending from Monterey to Sacramento. The Bay Area has a strong core-oriented public transportation system. However, as with most metropolitan areas in the United States, the suburban areas are highly automobile oriented and involve the usual problems for serving trips by transit.

The 18-county greater San Francisco Bay Area today has more than 30 public transport carriers with local, feeder, and express buses, ferries, light rail transit (LRT), rapid rail, commuter rail, intercity rail operating on freight railroad tracks, and potentially in the future

the California Corridor high-speed train service. Schedule coordination is spotty—mostly internal to a carrier, or bus-to-trunk-line-rail or bus-to-ferry connections. The study focuses on establishing a system of rail-to-rail transfers, with emphasis on possible near-term connections.

The model for the case study is the Swiss Federal Railway (SBB). The Swiss have developed a practical and cost-effective strategy to organize and maintain a comprehensive multihub timed-transfer public transport network for the entire country. The greater Bay Area, extending from Monterey to Sacramento, is similar to Switzerland with respect to population and distances between cities (see Figure 1). Also, the San Francisco Bay and the ridgelines of the Coast Range effectively constrain development, as do the lakes and mountains of Switzerland, creating transit corridors. Given this geographic similarity, establishing and maintaining a fully integrated multihub network of similar size and complexity appear feasible. The major difference for the Bay Area is the much higher automobile use with low-density, freeway-oriented land use. In summary, this case study investigates the applicability of the Swiss strategy for the more automobile-oriented greater Bay Area.

PULSED-HUB NETWORK OVERVIEW

The term used in this report for a Swiss-style comprehensive timed-transfer public transport system is a pulsed-hub network (3). Figure 2 illustrates the pulsed-hub network concept. At each hub the buses and trains converge in a scheduled “pulse” that provides travelers with timed transfers between all routes. Easy transfers at hubs give travelers “seamless” access to the entire public transport network; thus transfers become a benefit rather than something to be avoided. Moreover, a pulsed-hub network can integrate all transit modes from local buses to high-speed trains and a magnetic levitation system (maglev); provided, however, that the mode can maintain schedule reliability and that transfers at the hubs are quick and convenient.

Notice in Figure 2 that hubs are set a nominal 30 min apart, or roughly 27 min for travel time plus 3 min for transfer time. The distance between the hubs depends on the travel speed and schedule reliability of the transit mode—the faster the mode, the greater the possible distance between hubs.

In a multihub system, the timed-transfer pulses are coordinated by repeating the same base headway throughout the day. (Base refers to the off-peak schedule, and headway is the scheduled time interval between successive buses or trains.) For example, in Switzerland, the same base schedule repeats for about 16 h a day, 7 days a week. During peak travel demand hours, additional trips beyond the base headway are added as required.

In the Figure 2 example, only the primary hub-to-hub routes that operate on 30-min headways are shown. Routes that do not operate

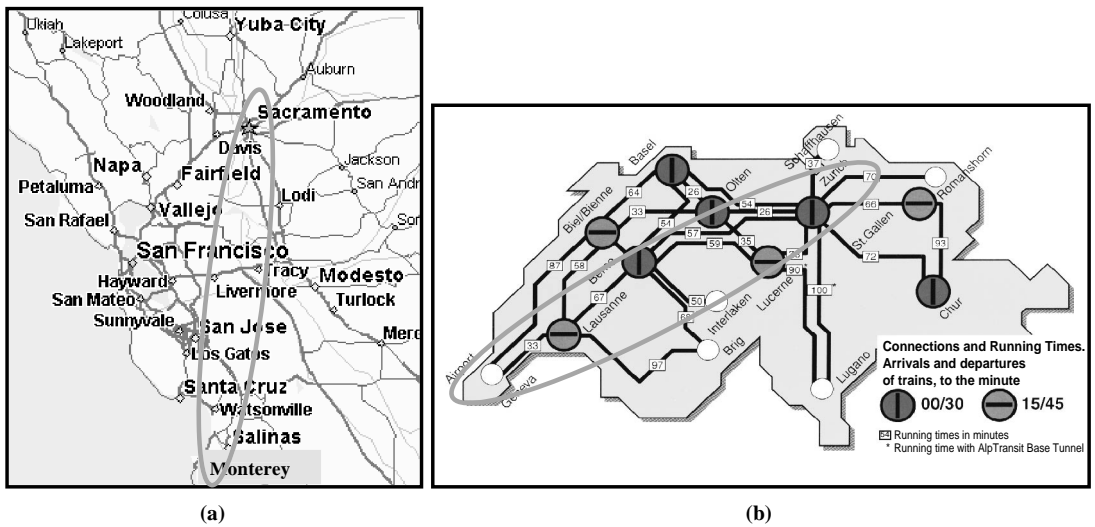


FIGURE 1 (a) Greater San Francisco Bay Area and (b) Switzerland. Monterey to Sacramento, 140 mi; Zurich to Geneva, 140 mi; population of Switzerland, 7.2 million; of Greater Bay Area (18 counties), 9.9 million.

on 30-min headways can also participate in the pulse, provided the route headway meshes evenly with a 30-min pulse, such as 10-, 15-, 60-, 90- or 120-min headways. Since these are all “clock-face” headways (the bus or train leaves at the same time or times every hour), they are easy to remember, and a user can quickly learn which trip to use to participate at the hub timed-transfer pulse.

Notice in Figure 2 that trains (or buses) traveling between two hubs meet halfway at the 15-min mark, which, therefore, could also be a hub station. Thus, in a pulsed-hub system, hubs can be spaced at one-half the headway. For example, if the base headway is 60 min, the hubs can be spaced 30 min apart. Or if the base headway is 30 min, the hubs can be spaced 15 min apart, or some even multiple, such as 30, 45, 60, or 75 min apart.

In summary, a pulsed-hub network is a multihub, timed-transfer system with a repeating fixed-interval clock-face schedule.

Swiss Strategy

SBB in its Rail+Bus 2000 Plan developed a cost-effective pulsed-hub network for the entire country. Figure 3 shows the Swiss plan projected to be in operation by 2005. This comprehensive pulsed-hub network, using intercity rail as the backbone, links all public transportation modes including high-speed trains, urban transit, buses, ferries, funiculars, cable-ways, and private railroads. In an era in which other public transportation services in Europe are losing patronage to

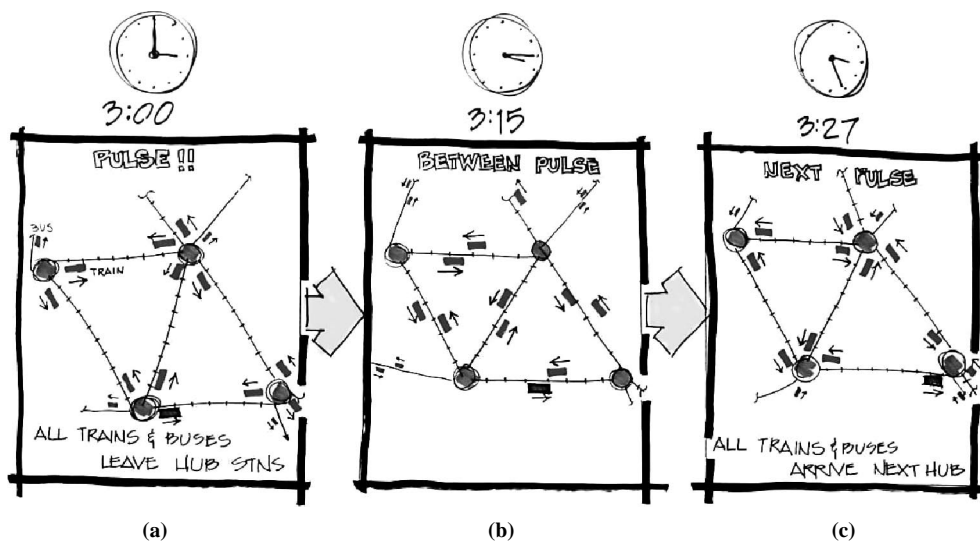


FIGURE 2 Pulsed-hub network concept: (a) all trains and buses leave hub stations in a “pulse” at approximately 3 p.m.; (b) all trains and buses travel between hubs; (c) all trains and buses arrive at hub stations at approximately 3:27 p.m., giving passengers approximately 3 min to transfer between routes.

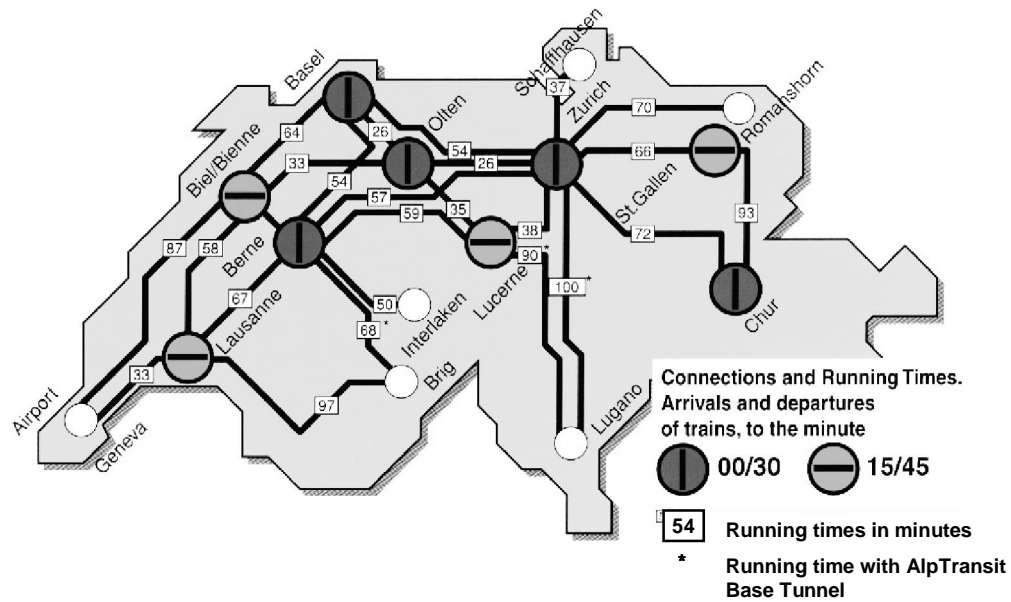


FIGURE 3 Swiss nationwide pulsed-hub network schedule map for 2005 (Rail+Bus 2000 Plan).

growing automobile use, Switzerland with its pulsed-hub network is holding its own.

SBB employed three analytical techniques, described below, which together simplify pulsed-hub network design and optimize investment requirements.

Schedule Map

In a pulsed-hub network, since the same basic schedule repeats throughout the day, it can be represented as a schedule map (see Figure 3). Note that the clock faces at each transfer hub indicate the nominal pulse transfer times, creating an easy-to-understand graphic. The travel times shown are for the express trains that connect between hub pulses. More detailed schedule maps that show local trains are also possible. Peak-period-only trips, such as commuter trains, would not be shown on a schedule map. In the development of a pulsed-hub network, the schedule map becomes an important communication

tool among planning, operations, patronage modeling (marketing), engineering, policy makers, and the public.

Symmetrical Time-Space Diagrams

Between each pair of hubs, the same schedule module, such as every hour, repeats throughout the day (see Figure 4). During each repetition of the schedule module the trains (or buses) leave at the same time, cross midway, and arrive at the other station at roughly the same time, creating a symmetrical pattern. The modular symmetrical time—distance diagrams, which graphically connect the schedule with the track plan and station platforms, are used to optimize investment requirements. First, for each hub-to-hub link, the symmetrical time—distance diagram for the busiest module of the day (or week) is identified and a window is assigned for each scheduled train, whether a hub-to-hub train, local train, commuter train, long-distance passenger train, or freight train. Second, the peak-period module for each hub-to-

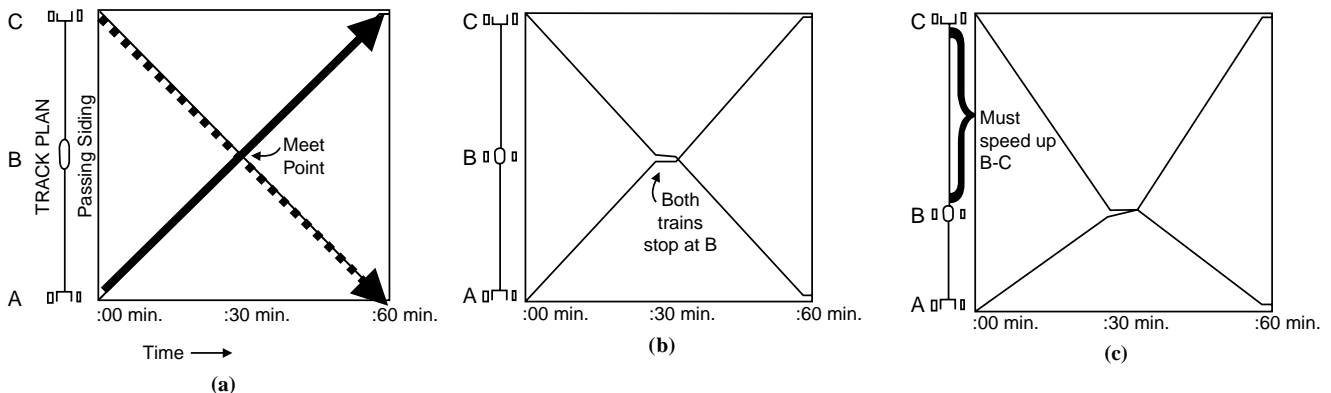


FIGURE 4 Modular time-space diagrams: (a) 60-minute module; (b) station at meet point; (c) offset midstation.

hub link is analyzed using train operation simulation tools to develop and test the minimum investments necessary to maintain the required hub-to-hub travel times and to eliminate any interference that might otherwise reduce the reliability of the timed transfers. By optimizing the design to serve the busiest module of the day or week, the design also optimizes by default all the other schedule modules of a week. This procedure greatly simplifies design and investment decisions.

“Only as Necessary” Investment Strategy

SBB is making investments in rolling stock and infrastructure (as in its motto) “only as necessary” to establish reliable timed transfers at the hubs.

For example, if hub stations are spaced 1 h apart, and the running time between two cities is currently 56 min (leaving 4 min for station dwell time and schedule recovery time), no investment is needed to make an hourly timed-transfer function. However, if two cities are 65 min apart, for the timed transfer to work, it is necessary to invest just enough to cut 9 or so min from the running time. Investing only as necessary, means starting with the least expensive improvement and then adding more expensive investments until the time transfers function reliably. Investments include new sidings to improve meets and passes, new rolling stock (e.g., tilting trains), signaling improvements, and so on. If that is still not enough, then major investments are needed, such as route alignment changes (including tunneling) or station reconstruction changes (such as adding new platforms or lengthening platforms).

Project proponents will always claim to be investing only as necessary, but with a pulsed-hub network, for the first time there is a precise criterion for investment—to invest only enough to establish reliable timed transfers at the hubs. Consequently, it is known exactly, not only whether a proposed investment component is adequate, but also whether it is still insufficient.

Viewing the system as a whole as a pulsed-hub network provides investment criteria by which to judge the cost effectiveness of each and every component, via a full systems analysis of capital costs, operations, schedules, and markets. In addition, the pulsed-hub network concept is understandable by the public, with the Swiss plan surviving two critical tests by the voters.

In summary, the pulsed-hub network and invest only as necessary strategy is a proven fundamental tool and approach to organizing public transportation.

Iterative Planning and Design Approach

The pulsed-hub network planning and design process is iterative, in contrast to the traditional process of successively narrowing the study and design focus to deliver a project. The traditional process begins with a regional systems study to select and prioritize corridors, then an alternatives analysis–environmental review to select the appropriate project for a corridor, followed by final engineering. However, since traditionally the transit schedule is developed only after basic engineering decisions have already been made, critical schedule connections may be missed. In contrast, the focus of the pulsed-hub network approach is on the coherence of the system as a whole—a system able to serve the many-to-many trip pattern of a region.

Since in a pulsed-hub network all components interact with each other, the design involves successive iterations of the decisions described as follows, while the schedule map, symmetrical time–space

graphs, and the “only as necessary” investment criterion described above are used as tools.

- Identify hub locations that are both network junctions and land-use centers. The ideal hub location is an existing downtown rail station that is already a transit focal point and a destination in its own right. Greenfield sites are problematic, since a critical mass of walking-destination land uses may not develop.
- Select a base headway. Hubs can be spaced at some multiple of one-half the base (midday) headway.
- Select a link mode, which is a function of speed, capacity, schedule reliability, and the existing mode (if any).
- Balance travel demand per link with the base headway, routings, mode, and consist sizes. May need peak-period trippers.
- Select hub station design with respect to the transfer walk times, dwell times, and schedule recovery times.
- Balance through-passenger wait time and dwell or schedule recovery time with the time needed for transfers.
- Distinguish full hubs (where all trains and buses from all directions wait) from partial hubs (where some trains and buses wait and others do not) and from directional hubs (with timed transfers between only certain directions).
- Balance operating costs with span (hours of day and days of week) of the repeating clock-face pulse schedule.
- Balance capital costs of infrastructure and rolling stock with reliable timed transfers at hub pulses.

In the planning and design of a pulsed-hub network, the first phase is complete when, after a number of iterations, the base headway and key hub locations are selected. The second phase is complete when the initial projects have been identified and prioritized.

BAY AREA PULSED-HUB NETWORK—ILLUSTRATIVE CONCEPT

On the basis of existing routes and schedules, future plans and prospective studies, and discussions with Bay Area transit planners and engineers (A. Zahradnick and R. Downing of Golden Gate Transit; J. Allison and D. Kutrosky of Capitol Corridor; A. Flemer and D. Kimsey of MTC; B. Capp of VTA light rail; R. Oto, C. Goodrich, R. Wier and D. Maxie of Caltrain; and W. Theile and D. Leonard of BART), an illustrative pulsed-hub network plan was developed (4–9).

Figure 5 shows the illustrative schedule map (illustrative plan) for the greater San Francisco Bay Area. This is not a final plan, but an illustration of how, using the existing and proposed public transport components, the pulsed-hub network strategy is able to maximize connections, both physically and in relation to the schedule, to best serve the public.

The running times in the illustrative plan are either current scheduled times or projected travel times based on planned improvements. As required for some hub pulse timings, further small running time improvements were assumed based on engineering judgment. The plan includes the existing Bay Area Rapid Transit (BART), Caltrain, and Capitol Corridor rail lines; the planned BART extension to San Jose; the proposed Sonoma-Marin Area Rail Transit (SMART) corridor using the Northwestern Pacific right-of-way; and the proposed rail connection across the Dumbarton Rail Bridge. Also, the whole plan would integrate smoothly with the proposed California Corridor high-speed rail plan.

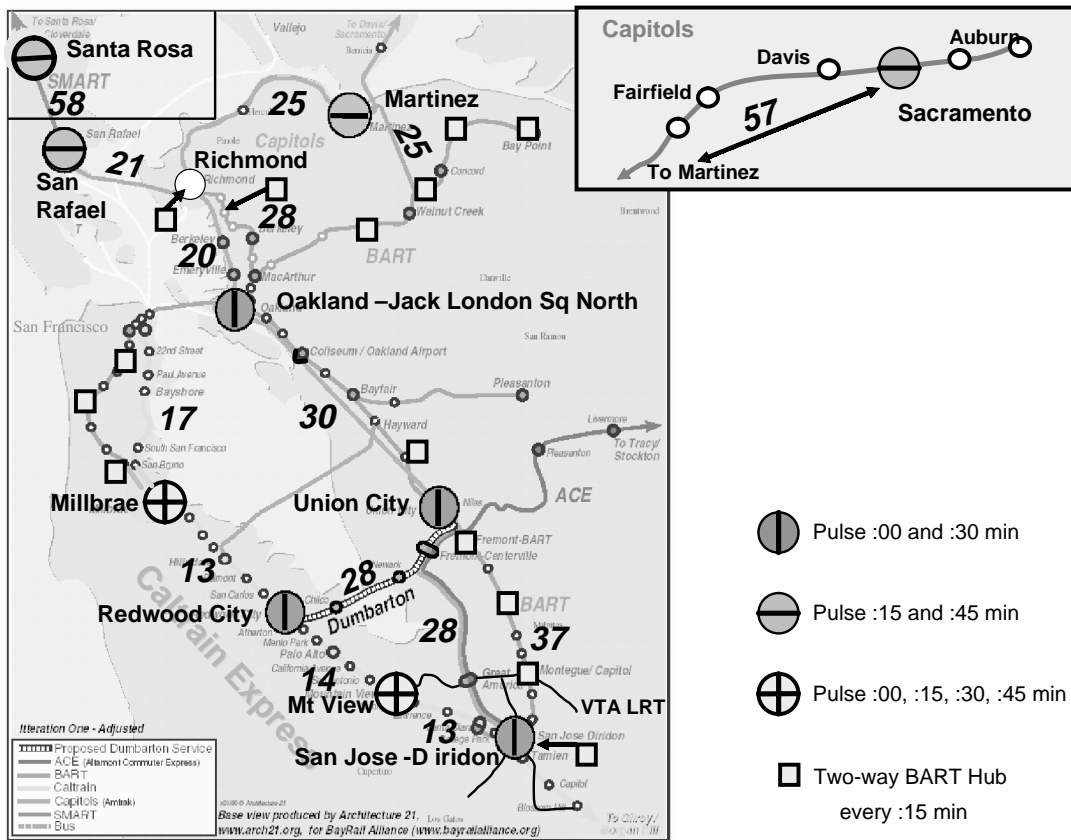


FIGURE 5 Illustrative plan schedule map for Bay Area pulsed-hub network.

Travel Times

The pulsed-hub network will save travel time for many trips, especially for longer and midday trips. Two examples follow:

- Today, for a midday trip between Redwood City and downtown Berkeley, a traveler would take the Caltrain local to San Francisco, transfer to the San Francisco Municipal Railway (Muni) Metro N line, and transfer again to the BART Richmond line, for a total trip time of 120 min. In mid-2003, when the Millbrae Caltrain–BART station opens, the trip will involve two transfers for an estimated 96-min travel time. With the illustrative plan, using Caltrain express service and BART and with a timed transfer at Millbrae, the two-transfer trip would take an estimated 81 min, or a similar time via the Dumbarton Rail Bridge with one transfer at Union City.

- Between Menlo Park and California State University, Hayward, a midday trip today would take about 110 min with three transfers. In the illustrative plan it would take about 85 min, also with three transfers.

Hub Locations

In Switzerland, existing downtown train stations provide obvious pulsed-hub locations; however, the greater Bay Area has only five obvious pulsed-hub locations that are or were downtown train stations: Diridon Station in San Jose, Redwood City Caltrain Station, the San Rafael Transit Center, and the Capitol–Amtrak stations in Mar-

tinenez and Sacramento. In addition, there are the joint BART–Capitol Corridor Station in Richmond and the soon-to-open joint BART–Caltrain Station in Millbrae. Unfortunately, the strong San Francisco Bay ferry system (which operated before the opening of the San Francisco Bay Bridge) inhibited the development of downtown rail stations in the core cities of San Francisco and Oakland. As a minimum, the pulsed-hub network would need a new hub station in Oakland to connect BART with the Capitol Corridor and proposed California high-speed trains. On the other hand, the short-range illustrative plan does not include a pulsed-hub in San Francisco, since the needed running time between the pulsed-hub at the Millbrae Caltrain–BART station and any downtown San Francisco station would require major investment to reduce curvature and increase speeds above Caltrain’s current 79-mph maximum speed. Also included in the illustrative plan would be pulsed-hub stations at the Mountain View Valley Transit Authority (VTA) light rail transit (LRT)–Caltrain, Santa Rosa SMART, and Union City BART stations.

Base Headway

The selection of a base headway for the network as a whole entails compromises relating to distances between the hubs, travel speed and schedule reliability of the hub-to-hub link modes, transfer times at the hub stations, and the market (ridership demand). Also, the selected base headway cannot be too different from existing transit service headways and span without significantly increasing operating costs.

For the illustrative plan, the selected base headway is 30 min for the inner part of the Bay Area and 60 min for intercity service to Sacramento. These headways are based on existing schedules and future plans (funded and unfunded) of the various agencies, plus any additional service that appears to be warranted either for patronage reasons or for the proper functioning of the pulsed-hub network. The following list outlines the existing and proposed service levels at five hub networks:

- The current BART 15-min service on each midday line meshes evenly with a 30-min base headway. Moreover, of the existing 312 midday bus routes that serve BART stations, 74% would mesh evenly with a 30-min base headway.
- The proposed Caltrain service levels of 30-min headways for both local and express services are ultimately achievable, and when combined they would match the 15-min BART service at Millbrae.
- Hour headways are projected for the Capitol Corridor, after completion of the planned improvements, both funded and unfunded (9). In addition, there are plans for supplemental Capitol service to improve peak service to 30-min headways.
- The Dumbarton Rail Bridge service is assumed to be local trains with 30-min midday service to match Caltrain service at Redwood City and the Capitol at Union City.
- Golden Gate Transit has a 30-min hub pulse for buses at the San Rafael Transit Center.

Timed Transfers and Schedule Reliability

Since timed transfers require schedule reliability, the first investments for a pulsed-hub network should focus on improving reliability rather than speed. BART has the best rail service schedule reliability in the Bay Area. The illustrative plan invests in reliability improvements for Caltrain and the Capitol Corridor, so that they can join BART as partners in the pulsed-hub network.

BART

The illustrative plan restores the BART cross-platform timed transfers between the Richmond–Fremont and Colma–Pittsburg–Bay Point lines, and improves transfers at the Bay Fair Station between the Dublin–Pleasanton line and the trains running to and from Fremont. The throughput capacity of the Oakland Wye, used by all lines, constrains any other changes in the schedule. The schedule changes are based on an estimate of the travel time improvements associated with the proposed signal system, plus schedule coordination between BART and Caltrain at the Millbrae station.

The illustrative plan assumes a new BART station at Oakland in the north end of Jack London Square, with direct connections to the Capitol Corridor trains and proposed California Corridor high-speed trains.

Currently, BART operates all lines with 15-min headways during the day (plus some peak trippers) and 20-min headways on nights and weekends. In the illustrative plan, BART's contribution to support the pulsed-hub network would be to maintain the same 15-min headways for days, nights, and weekends. This change would provide better service for BART riders, and provide a consistent schedule for establishing timed transfers between BART and all connecting operators. At night, to bypass track maintenance, BART uses single track running between crossovers, but in the oldest parts of the BART system the crossovers are spaced too far apart for any headway less than 20

min. Constructing additional crossovers would allow 15-min night-time headways. The approximate cost for an estimated 10 additional crossovers is \$250 million, and \$8 million annually in additional operating costs (in 2001 dollars) for the 15-min headways.

Caltrain

Caltrain is constructing four-track sections in three locations to allow express trains to bypass the local trains. Locals currently take 90 min for the 46 mi between San Francisco and San Jose. One of the timetables developed in planning the express train service is shown in Figure 6. The illustrative plan for Caltrain uses this same schedule with one modification. Instead of the local trains waiting about 8 min in a siding south of Redwood City for the expresses to pass, the local trains would wait for about 5 min at a new four-track Redwood City Station. Redwood City, located halfway between San Francisco and San Jose, would function as a pulsed-hub station with cross-platform transfers between local and express trains and with the proposed Dumbarton Bridge line.

The illustrative plan Caltrain 30-min headway express and local services would arrive at Millbrae Station approximately 15 min apart. That would enable a timed-transfer pulse with the 15-min headway BART trains and BART–San Francisco International Airport shuttle. A similar 15-min pulse timing for Caltrain at Mountain View Station would improve connections with the Santa Clara VTA Tasman LRT line.

For the Caltrain commuter railroad to function effectively in a pulsed-hub network, the major sources of schedule deviation need to be eliminated: the hold-out rule and the use of wayside lifts for handicap boarding and bicycle loading, as described in the following list:

- Caltrain currently has 13 stations with side platforms, on which a passenger can walk across the two sets of tracks. A passenger wanting to cross the tracks runs the risk, after waiting for one train to pass, of not seeing the second train on the other track. The hold-out rule keeps a second train from entering a station until the first clears. Eliminating the hold-out rule requires either a fence between the two tracks, or a center platform with a grade-separated walk access.
- Handicap and bicycle boarding can be greatly improved by having at least one low-floor car per train and raising the platform height above the current 8 in. above top of rail. Unfortunately, as currently configured, the new low-floor tri-level cars (with an entrance 22 in. above top of rail) are not compatible with the existing fleet, and so need to run in separate trains. Therefore, either the new or old cars would need to be reconfigured so they can work together, or a new fleet would have to be purchased. In the long-term, purchasing a new fleet is feasible, because the current plan to electrify the line requires new electric multiple unit cars (D. Maxie, unpublished data).

Dumbarton Bridge Rail Service

The proposed Dumbarton Bridge rail service plan estimates a 35-min rail travel time between the Union City and Redwood City stations, with three intermediate stops (D. Maxie of Caltrain, unpublished data). To obtain a reliable less than 30-min run time, track and station improvements will be required, including a separate track and platform for the Dumbarton service at both end stations, track improvements already identified for Capitol Corridor service, and a track flyover at the Newark junction.

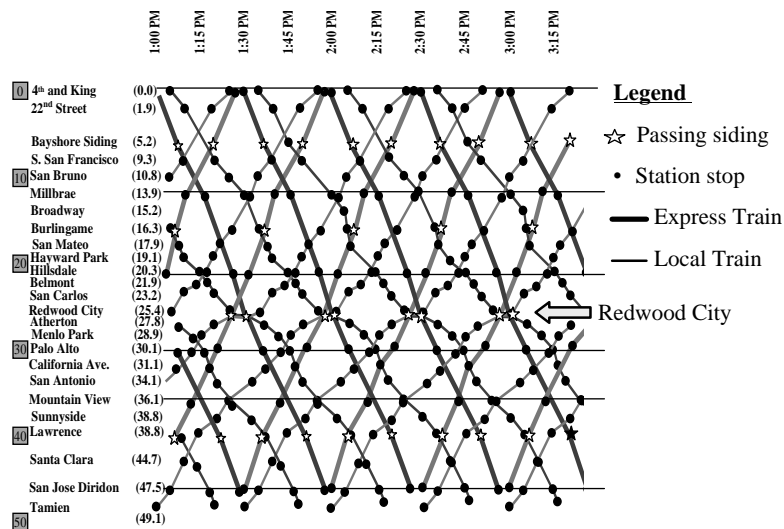


FIGURE 6 Caltrain express and local operating plan concept with passing siding at Redwood City. In the illustrative plan Redwood City becomes a hub, with cross-platform transfers between locals and expresses running in the same direction, and with walk connections to the Dumbarton Rail Bridge train, trains running in the other direction, and the SamTrans bus transit center.

Capitol Corridor Service

The illustrative plan Capitol Corridor running times are based on the “intermediate” capital improvement plan (9) with the following additional improvements: a Union City station and new Shinn connection to use the Western Pacific tracks; eliminating the Hayward station, which is lightly used and does not connect with BART; a new Oakland station north of Jack London Square that is approached via a tunnel to avoid the current street running in the Jack London Square area; and unspecified improvements between the new Oakland station and the Richmond station.

The Capitol Corridor intercity trains operate on freight railroad tracks. The two main sources of schedule unreliability are the drawbridges over the Sacramento River and the Carquinez Straits (between Martinez and Benicia), and interference from freight trains. A conceptual estimate to replace the drawbridges was under \$300 million (9). There are three ways to reduce freight train interference:

- Increasing infrastructure capacity to improve operational reliability, which the Capitol Corridor Joint Powers Board (CCJPB) has been doing. The CCJPB has additional plans, subject to negotiations, for yet further improvements.
- CCJPB could construct its own tracks, as described in the Capitol Corridor Vision Projects, for an exclusive San Jose-to-Oakland passenger corridor for a conceptual estimate of \$200 million (9).
- The freight railroad could operate on a schedule with timed windows for freight as well as passenger service. The modular schedule of a pulsed network makes it much easier to establish scheduled freight trains. Moreover, a modular schedule significantly simplifies freight railroad negotiations into a potentially win-win situation. First, for the worst schedule module of the day or week, a window for each freight and passenger service is identified, and then simulation models are run to exactly define the minimal investment needed to provide reliable passenger service. This public investment provides the freight railroad

with improved reliability during all hours and improved capacity during off-peak hours.

It is possible that the freight railroad will be unable to change its culture to allow scheduled freight trains, thus inhibiting reliable timed transfers. In that case the illustrative plan could be changed so that BART rather than the Capitols provides the hub-to-hub links in the East Bay (San Jose to Richmond). This change would provide service that is not as fast, but it may be more easily implemented.

SMART Corridor

The proposed SMART will own and operate its own system and so should maintain excellent schedule reliability. Although current plans for running on the Northwest Pacific rail right-of-way call for peak-only service, congestion along the parallel US-101 freeway suggests that all-day service may be warranted between San Rafael and Santa Rosa.

California High-Speed Rail

The current conceptual operating schedule scenario for the proposed California Corridor high-speed rail service indicates a 2-h timing for a nonstop express train between the Los Angeles Union station and the San Jose Diridon station. Both stations are ideal downtown hub locations and also key nodes in the network. At Diridon, the proposed high-speed service would split, running up the West Bay to San Francisco and up the East Bay to Oakland. Moreover, both stations have regional rail connections, as well as existing or proposed rapid transit service. The critical point is that this 2-h schedule would allow for clock-face pulse schedules at both stations, enabling them to serve as gateway timed-transfer hubs for their respective regions.

DISCUSSION AND FINDINGS

Institutional Issues

This research has prioritized the issues concerning potential institutional problems associated with the multiple transit agencies in the greater Bay Area. First, develop what might be called the maximally feasible cooperative arrangement for the public transport system as a whole—a route structure, schedule, and hub stations, in which all components support each other. Second, make financial and institutional arrangements that are needed to support the pulsed network. This procedure puts the focus on the good of the region as a whole, while potentially maximizing the patronage of each operator. Consequently, the study focused on developing a technical solution that integrates the various agencies into a fully cooperative regional system. Only after a viable regional solution has been shown to be technically possible, cost-effective, and desirable will it be possible to garner the political will to make any necessary institutional and funding changes. That said, some observations concerning possible institutional arrangements are offered as follows.

- All public transportation agencies in California depend on public subsidies, since none can pay even for their operating and maintenance costs out of the fare box. A state law allocating a certain percentage of the subsidies to transit coordination with other agencies should effectively induce cooperation. The law could include some fare-sharing arrangement that rewards both carriers for passenger trips served by both.
- Schedule coordination for metro regions with multiple transit agencies becomes easier with a pulsed-hub network, since each agency would find it advantageous to schedule its service to match the hub pulses. This process automatically schedules timed transfers between the routes of neighboring agencies.

In the long term, politicians and policy makers will make the necessary institutional changes and find the necessary funding only if the regional public transport integration plan is understood by the voters and the public at large. In the short term, however, the plan needs to be accepted by the existing public agency staffs, policy makers, and users. Thus, the multiple transit agency situation presents a fundamental planning dilemma of vision versus practicability—a system plan needs to be bold enough to capture and sustain public interest, yet able to be implemented via incremental modifications acceptable to existing agency staffs and riders. It is suggested that a pulsed-hub network potentially provides the vision, boldness, and practicality needed for acceptance.

Station Design and Transit Network

The tighter the hub walk distances, the more effective the pulsed network. Through travelers will tolerate short dwell times while passengers transfer between lines. However, a long transfer walk may make the timed transfer untenable because of the long dwell times. For example, the more than 1,000-foot distance between the proposed downtown San Francisco train station at the current Transbay Terminal Site and the BART and Muni metro trains under Market Street is too long for a timed transfer. In particular, the Diridon station in San Jose connecting Caltrain, the Capitols, Altamont Commuter Express, and VTA light rail is becoming the most important hub in the Bay Area. With the proposed high-speed train connection to Los Angeles

it would become the gateway to the Bay Area, with the potential of becoming a world-class facility. For the network to function at its best and maximize patronage, it is important that the proposed BART extension station be tightly connected to Diridon Station, to allow timed transfers between BART and the other services.

Hub Locations and Hub-to-Hub Running Times

The repeating clock-face base headway of a pulsed-hub network creates relatively rigid time—space relationships. South of Oakland, the hub spacing along the Caltrain and Capitol routes works well with 30-min service and 79-mph top speeds, since the hubs are about 30 min apart. North of Oakland, however, the Richmond BART–Capitol hub station does not work as well, since the travel time between Oakland and Richmond is about 20 min, and reducing the travel time to under 15 min to match will require significant investment.

The illustrative plan travel times and timed transfers provide 45-min service between Oakland and San Rafael, and between Oakland and Martinez, but not between San Rafael and Martinez, which would take 1 h with a layover at the Richmond station. Distances between the Richmond hub and the San Rafael, Martinez, and Oakland hubs are not that great, but making all connections 15 min apart requires the following: The least expensive approach would be high-occupancy vehicle (HOV) lanes (some elevated) between Richmond and San Rafael. A tunnel between Richmond and Martinez (or between Richmond and Hercules) is contemplated by the Capitol Corridor, since it would significantly shorten the travel time between Oakland and Sacramento. Improving the rail connection between Richmond and Oakland may require a tunnel under West Oakland and grade separations. Alternatively, instead of the new joint BART–Capitol high-speed train station north of Jack London Square assumed in the illustrative plan, construct, instead, a Capitol high-speed train terminal under the 12th Street BART station. A tunnel under West Oakland for the Capitols would also be required.

Pulsed-Hub Network Design Envelope

This study is a step toward defining the transit operations–capital cost–operating cost–patronage envelope in which the pulsed-hub network approach is appropriate. The following recommendations are offered:

- Headways. For urban areas with close-headway transit routes, timed transfers are not needed. On the other hand, for areas with longer headway routes such as intercity travel and much of suburbia, timed transfers are a significant benefit. The pulsed-hub network approach with a repeating base headway brings isolated timed-transfer hubs into a coherent system.
- Hub-to-hub distances. For rail service, the study suggests that the longer the distances between hubs the easier it is to plan and construct a pulsed-hub network, and that with shorter distances between hubs capital costs may increase significantly.
- Speed. In a large region, using the fastest mode between hubs can capture choice riders. Speed “stretches” the network so feeder routes are less likely to meander as they do in some timed-transfer bus systems. Obtaining the necessary running time to meet the timed-transfer pulses may require reducing the number of stops along a line. Consequently, hubs should be at destinations with mixed land use and walking trips. If at all possible, greenfield sites should be avoided (10).

- Scalability. High-speed train integration into the illustrative plan emphasizes the point that a pulsed-hub network can start small and expand in any direction as new hubs and new services are developed and integrated into the network.

In summary, the study suggests that a metropolitan or larger region is an appropriate geographic area to implement the pulsed-hub network strategy.

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