Public Transport Priority for Brussels:
Lessons from Zurich, Eindhoven, and Dublin

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1 Introduction

Priority for public transport is an objective of Brussels and other large cities. It is the key to breaking the vicious cycle of congestion that threatens to bring cities to gridlock. In that cycle, increasing private traffic makes public transport become slower and less reliable, especially because while motorists are free to seek less congested routes, public transport lines cannot simply change their path, and therefore suffer the worst congestion. The resulting deterioration in public transport speed and reliability induces more people to abandon public transport in favor of the private car, making congestion still worse. Giving public transport *congestion protection* breaks the vicious cycle, and makes public transport more and more attractive as cities and traffic pressure grow. A traditional way of protecting public transport from congestion is to put in underground, in the form of a metro or premetro; however, the enormous expense involved limits that solution to a few travel corridors. For the rest of the public transport network, consisting of surface routes run with buses and trams, congestion protection takes the form of public transport priority.

Increasingly, cities look to advanced engineering solutions for ways of achieving their vision of public transport priority, without imposing an undue burden on general traffic, which also serves social mobility needs. Advances in computing, detection technologies, and communication permit more intelligent and efficient methods of traffic control in general, and of public transport priority in particular.

In this context, every city is a laboratory, testing methods of granting priority to public transport. Brussels is a leader in some forms of public transport priority, but in other areas, particularly those relating to traffic signals, Brussels is not. At this time, the Brussels Region is contemplating both modernizing its traffic signal system and increasing application of signal priority. Therefore, learning from cities that are leaders in public transport priority applications is particularly relevant to Brussels. This report documents a project investigating public transport priority provisions in Zurich, Eindhoven, and Dublin, and applying its lessons to Brussels.

Zurich is known internationally as leading example of public transport priority, where public transport experiences “near-zero” traffic delay. However, little detail of Zurich’s engineering solutions has been documented (Nash (2001), Oehrli (2002), and Ott (2002)). Except for Nash, which has more of a planning than engineering perspective, these reports were written by Zurichers. The external perspective of this report may therefore be a valuable addition.

Eindhoven, in the southern part of the Netherlands, is known in traffic engineering circles as a city with both an aggressive program of public transport priority, with near-zero traffic delay for public transport, and a reputation for innovation. It was the first city to adopt conditional priority (priority only to late buses), together with fine tuned scheduling tools, as a means of operational control (Furth and Muller, 1999). More recently, it has adopted the proprietary control system SPOT-Utopia in part of its network. SPOT-Utopia is an areawide traffic signal control plan that applies many advanced methods of intelligent transportation systems. A review of that system therefore has much to offer. In this context, Eindhoven stands as a representative of other cities that have applied SPOT-Utopia, among which the most extensive application is Turin, where SPOT-Utopia was originally developed.

Dublin is a relative newcomer to the field of public transport priority. A recent bus lane program (“quality bus corridors”) has had great success. Public transport signal priority there, begun in 2004, is limited to two new light rail lines, but this system serves those lines with nearly no traffic signal delays.

Brussels, too, has considerable experience in public transport priority, most of it in measures unrelated to traffic signals, such as reserved lanes. It has an aggressive program of public transport improvement on both the side of STIB (the public transport company) and the Regional government.

Chapter 2 of this report provides background on the cities studied. Chapter 3 presents the Zurich vision of urban traffic control. It is a unified vision encompassing many aspects of public transport priority, and so its experience is used as an outline in many of the chapters that follow.

Chapter 4 describes policies and practices that help limit general traffic – a vital part of giving priority to public transport. Chapter 5 discusses how the design of reserved lanes affects their ability to achieve their goal of isolating public transport from traffic queues. Chapter 6 discusses circulation and traffic metering techniques that reduce traffic locally on public transport routes. Chapters 7 and 8 covers details of signal control in Zurich: queue management, and active signal priority.

Chapter 9 covers Dublin’s signal priority. Chapter 10 analyzes the advanced methods of signal control used by Eindhoven and Turin. Chapter 11 discusses options for signal control program management in light of the Brussels Region’s interest in improving its signal control.

Chapters 12 offers conclusions. In addition, beginning in Chapter 4, there are frequent sections entitled “Application to Brussels” that offer both general and specific recommendations for applying the principles discussed to improving public transport priority.

2 Background

ZURICH

The city of Zurich is the center of a metropolitan area with population 1,000,000 (380,000 in the city) and employment 600,000 (330,000 in the city). It has an extensive tram network supplemented by bus lines; an extensive regional rail (S-Bahn) network; and some smaller operations (mountain railways, lake ferries). Transportation policy is affected mainly by the City of Zurich.

Like the rest of Switzerland, Zurich has a lively, participatory democracy. Debates about transportation policy are vigorous and are often settled by popular vote (referenda). One well-known result of the democratic process was the 1973 rejection of plans put forth by city officials to build a subway, and adoption in 1977 of an investment plan for improving its surface transportation system, largely trams along with some bus lines.

From this democratic process has emerged a rather unified set of policies favoring public transport. Like many other cities, Zurich is committed to limiting growth in auto traffic while still promoting economic growth, meaning that public transport must carry more and more people and an increasing share of trips. Prevented from investing in public transport the conventional way (by building a metro to bypass congestion), Zurich was forced to find ways to give it priority on the street, and has become a leading example in practice of giving priority to surface public transport.

DUBLIN

Metropolitan Dublin has a population of 1.5 (1.1 million in the official Dublin Region comprising the former Dublin County), and employment of 680,000. It has an extensive bus network operated by a private company, Dublin Bus, with government subsidy; frequent regional rail service along coastal routes north and south; and less frequent regional rail service with a few routes reaching into the island. Since 2003, it has a brand new tram (light rail) system called Luas (*“speed”*) with two lines, funded and managed by a subsidiary of the federal government.

Dublin began an aggressive program of bus priority in the mid-1990’s, creating Quality Bus Corridors whose chief priority feature is exclusive lanes (O’Mahony, 2002). This program, applied to more than a dozen corridors, has been a huge success in both improving running time and attracting new riders.

Signal priority is a new program in Dublin, having begun in 2004 and limited to its two new tram lines.

EINDHOVEN

Eindhoven is a city of 200,000 people in the south of the Netherlands. Because of its moderate size, and because much of the city has a generous road network because it was built after the advent of the automobile era, its traffic congestion is mild compared to the other three cities in this report.

Eindhoven has been an innovator in public transport priority for many years, and has recently become the largest site in the Netherlands for implementing the areawide intelligent traffic signal control program SPOT-Utopia. Originally developed for Turin, where it is most extensively applied, SPOT-Utopia’s application in the

Netherlands has led to several enhancements. In this report, Eindhoven is used as a representative of traffic signal control using SPOT-Utopia.

BRUSSELS

Brussels is the center of a metropolitan area with population roughly 2.5 million, with 1.1 million in the official Brussels Capital Region comprised of 19 communes. Employment is 680,000 in the metropolitan area, including 380,000 in the Brussels Capital Region. The public transport operator in the Capital Region, STIB, has three metro lines and an extensive network of trams and buses. Some sections of tram line are in tunnel, called premetro.

STIB operates under a management contract with the Region. As part of this contract, the region is committed to making improvements to the surface STIB network, mainly in the form of reserved lanes.

The Region has had since 1991 a program VICOM (for *vitesse commerciale*, or commercial speed) for improving the speed and reliability of public transport on surface streets. Its vision for public transport priority is laid out in a report jointly prepared with STIB, *Feu Vert aux Transport Publics* (STIB, 2003). STIB, in turn, has an advanced system of quality control and service quality certification, and takes a pro-active approach to improving facilities for surface routes as well as for grade separated routes. Its *Vision 2020* (STIB, 2004) includes many recommendations for priority improvements. In 2005, it began an annual program of formally reporting to the Region a list of *points noires* or “hot spots” where surface public transport suffers the most from congestion (STIB, 2005).

Responsibility for many streets, signals, and traffic law enforcement in the Brussels Region rests with the communes, whose leadership is not always as supportive of public transport priority as the leadership of the regional government. The communes’ lack of agreement has forced the cancellation of some priority projects, and stands in the way of others. STIB continues to try to work with the communes to get their cooperation in improving public transport service.

3 Zurich’s Vision for Urban Traffic Control

Zurich’s rejection of a metro and adoption instead of a policy of priority for surface public transport has led them to develop a unique vision of how traffic should be controlled in a city. While some road segments prohibit cars, being reserved for either pedestrians or public transport or both, and while many roadway lanes have been made exclusive public transport lanes, Zurich has pursued a vision of traffic control in which pedestrians, public transport, and general traffic peacefully co-exist.

First priority goes to pedestrians. That also helps public transport, since their customers all start and end as pedestrians. Serving them well means short signal cycles. Where possible, they keep cycles down to 45 s, and rarely exceed 60 s, in order to limit how long crossing pedestrians have to wait for a walk signal. While the Swiss are known for being orderly, they are no more immune from human impatience than anyone else, and have a much smaller tendency to violate a “Don’t Walk” signal if the wait for the “Walk” signal is short.

Having short cycles, in turn, demands having (1) compact intersections with short crossing distances and (2) preferring 2-phase control where possible, i.e., not having protected left turns. In recent years, they have shrunk many intersections, creating additional pedestrian space at the same time. Successful 2-phase control, in turn, is helped by short cycles, since phase endings allow cars to turn even when opposing traffic is strong.

Public transport should not be hindered by traffic. It should operate in its own lane in order to not be hindered by queues, and it should have priority at signals.

General traffic flow should be neither fast nor slow. Fast is dangerous, and because of the universal desire to save time, it attracts more traffic. Therefore, cars should have a small delay at each intersection, which has two strong benefits: it compresses the queue, thereby making green time more effectively used, and it makes it such that the traffic passing intersections is going at a slow pace, not passing through at cruise speed.

Slow traffic is to be avoided not only because it is frustrating to drivers and polluting, and therefore bad for pedestrians. On streets used by public transport, slow traffic with long queues hurts public transport. This is obvious when public transport shares a lane with the queued traffic, but is also true when public transport has its own lane. Long queues increase pressure to trespass onto a public transport lane; they lead to left-turning vehicles standing in the public transport lane, waiting for a gap to either enter or cross a queue. For similar reasons they lead to accidents, which have an especially devastating effect on tram operations since trams cannot make small detours around immobilized cars.

public transport also benefit from short queues because they permit greater flexibility in giving priority at traffic signals. When signals are interrupted to let buses and trams pass without delay, they can more quickly recover, so that transit priority becomes hardly a burden to general traffic.

Zurich’s traffic control uses a concept of managing and processing queues and platoons. Short signal cycles allow small platoons of 6 to 10 cars per lane to pass each cycle. Platoons advance through successive intersections with a little delay at each, the delay serving to compact the platoons, and to limit the speed of traffic at intersections. With such control, queue lengths are roughly limited to the platoon size, keeping them from interfering much with public transport.

Zurich has adopted a policy of pursuing their ideal traffic regime where it matters the most – in the urban center, where sidewalks and trams carry more people than cars. Pedestrians enjoy short cycles; public transport has nearly no delay from traffic (except approaching the two main transfer stations, where the hindrance comes from lack of station capacity and conflicting tram lines); and general traffic advances in small platoons, frequently delayed, but not by much. Queue lengths are roughly limited to the platoon size, keeping them from interfering much with public transport.

This ideal traffic regime will only support a certain amount of circulation – less than could be accommodated if one were to permit wider intersections, longer queues, longer signal cycles, and greater public transport delays. Therefore, another side of Zurich's model of control is applying policies to limit traffic, both globally and locally.

4 Policies for Global Traffic Reduction

The challenge of giving priority to public transport depends on the level of general traffic. When there is a lot of traffic – as in Belgium, where auto ownership grew by a factor of 7 between 1960 and 2000 – traffic pressure creates a multitude of hindrances to public transport. More importantly, beyond a certain level of traffic, concerns about traffic capacity outweigh those of public transport priority, because if capacity needs aren't met, the whole city can become stuck in gridlock, immobilizing public transport at the same time. Therefore, policies that help reduce the amount of general traffic are an important part of public transport priority. (These policies are synergistic, since public transport priority contributes to reducing the amount of general traffic.)

The value of reducing traffic globally can be readily seen in Zurich, where twice as many daily trips are made by public transport as by car (600,000 versus 300,000), making Zurich's public transport share for work trips (56%) double that of comparably sized European cities. (Brussels' public transport share, by comparison, is 30% of work trips.) In Zurich, public transport is attractive for non-work trips as well, making its per capita public transport usage (550 trips per year) roughly double that of even London and Paris. Zurich's high public transport share and low auto use is not an accident or a quirk of "being Swiss" that cannot be transferred to other nations; rather, it is the result of deliberate policies that others can learn from. Until 1992, auto use in Zurich was steadily climbing. Since 1992, however, effective transport policies have kept the number of daily car trips constant in spite of steady economic growth, with growth in public transport use making up the difference. A visitor looking to see how public transport is given priority over general traffic notices foremost the *lack* of traffic along most public transport routes. Zurich still has streets and corridors with persistent congestion problems; however, the traffic levels on many of its public transport routes low enough to make certain priority tactics feasible that otherwise would not be.

Like many other cities, Zurich ensures that intense office and commercial development takes place where it can be well served by public transport. Besides these important land use policies, three policies stand out as contributors to Zurich's low automobile trip rate.

4.1 Limiting Parking

Transportation planners agree that the cost of parking is the most important single determinant of mode split. The number of parking spaces in the city center may not exceed its 1990 count. New developments can include parking spaces only with arrangements to remove an equal number of spaces elsewhere (most often, by removing on-street spaces). As a result, parking in the city center is both hard to find and expensive.

4.2 Investing in High Quality Public Transport

The second most important thing to getting people to not drive is offering high quality public transport: fast (relative to the distance involved) and reliable. For people living and working in the area covered by the tram network (roughly a radius of 7 km from the center), this objective is met by having a high frequency and dense network of tram and bus routes, protected by priority from traffic congestion.

Making public transport attractive at greater distances requires modes with higher speed. Zurich has long had rapid train service to the city center; however, until 1992, that train service was only attractive to a rather limited set of origin-destination pairs, because there was no connection between the train stations on either side (northwest and southeast) of the city center. With the growing number of long distance commuters came more and more auto traffic, whose destination was not the city center (well served by train and with limited parking), but in parts of the city outside the center.

In 1992, the completion of a tunnel joining train stations on either side of the center, together with increased frequencies in a newly named S-Bahn (regional rail) service shifted growth from the auto to public transport mode. The chief advantage of the new system was allowing one to take a train from anywhere in the metropolitan area to any station in the city, including stations on both sides of the center and four stations outside the center serving heavy employment centers. For many travelers, S-Bahn serves both as the line haul mode (into the city) and the distribution mode (within the city), where the latter function was formerly provided by (slower) trams. In some ways, the S-Bahn became the metro that Zurich rejected 25 years earlier; however, because of its long station spacing, it does not replace, but rather complements, the tram network.

What does building a train tunnel have to do with priority for buses and trams? Directly, nothing; but indirectly, a lot – by getting commuters out of their cars, it has made the streets much more hospitable places for operating trams and buses.

4.3 Periphery Metering

Zurich's traffic engineers have realized that efforts to give priority to trams and buses can be drowned in a sea of congestion. To complement policies that persuade people not to drive into the city, Zurich uses traffic signals to meter the flow of traffic entering the city on key arterials at the periphery of the city. About 20 roads entering the city are metered by express limitations on greet time; they covering about 80% of the incoming traffic. (Some traffic enters on local streets that are not metered.) The result is to transfer queues to the periphery, keeping the center mostly clear of queues.

Zurich keeps its metering program at a level that makes it almost invisible to the general public. Capacity is limited in ways that don't look obvious. For example, a few extra seconds are given to a pedestrian phase, or the fraction green time is reduced by reducing the cycle length. As a result, there is little public awareness or controversy involved in this program.

London is well known for accomplishing periphery metering through its congestion charge program. Compared to Zurich's, London's system covers a much smaller part of the city, relieving congestion in the inner part of the city, but not in the nearby, older suburbs that are still heavily congested. Also, London's method of metering is rather expensive to operate (of the UKP 5 per vehicle paid in 2004, about half went to operating the system); Zurich's system has nearly no direct cost.

On a historical not, one could say with some irony that peripheral traffic metering and congestion charging is nothing new, but rather an ancient practice known in every medieval city, where traffic could only enter the city through gates in the city wall, and tolls were charged for heavy traffic (merchandise). Even after Brussels' walls were demolished, a fence along the Petite Ceinture still allowed entry to the city only at the ancient gates, where tolls were still collected, until about 1880. The former Porte de Namur tollhouse now stands at the entrance to the Bois de la Cambre.

APPLICATION TO BRUSSELS

The Brussels Region's long term mobility plan recognizes the need for overall traffic reduction, calling for a 20% decrease in auto use relative to 1999. Zurich's example shows that it can be done, and offers some guidance.

First, Brussels faces an enormous problem in trying to reduce automobile use: the fact that national tax rules and business practices give employers have a strong incentive to provide employees with autos. Of course, for employees to receive this benefit, they have to use the autos to travel to work. As a consequence, 35% of the cars used by peak hour commuters are company owned (STIB *Vision 2020*)! Fiscal policy should be revised to eliminate this perverse incentive, perhaps by imposing a tax on company cars large enough to eliminate its advantage. (And if companies still wish to offer employees this benefit, the tax revenues should be directed to supporting public transport.)

Like Zurich, Brussels' surface public transportation system would benefit greatly from stricter parking limitations within the pentagon and nearby high-employment districts.

Many reasons have been advanced for investing in expanding Brussels' public transport network. This report adds one more reason: it will improve the quality of surface public transport, both by causing a general reduction in congestion, and by increasing opportunities for priority treatments. A regional rail system ("RER") is already planned, although it should be noted that the chief benefit Zurich saw from its regional rail project is something that Brussels has already been enjoying since its North and South stations were joined in 1952. More urgently needed are extensions of the pre-metro to Schaerbeek (Vanboekhoven, with a branch to Rogier / Haecht) and to Uccle's Alsemberg corridor. These corridors are among the worst served by public transport, and have the worst traffic problems affecting bus and tram routes. Extensions of the pre-metro will get a lot of Schaerbeek and Uccle travelers out of their cars, improving surface public transport operations in both communes and throughout the Region.

With a limited number of arteries carrying most of traffic that enters the city, Brussels' road network is well configured to support to a program of traffic metering. Already, Brussels meters traffic at three entry points, although the focus of this program has not been public transport operations. Experiments should be conducted (whether with actual metering, or with traffic simulations) to determine to what extent further application of peripheral metering would reduce queues that hinder bus and tram operations, and to apply metering that proves beneficial.

5 Exclusive Lanes and Self-Enforcing Designs

The most direct way of giving priority to public transport is to give them exclusive lanes. This is analogous to putting public transport vehicles into a priority queue – at any traffic signal, they advance to the front of the queue.

Putting public transport vehicles into a priority queue demands physical space that is often lacking in a city whose streets were built in an era of much less traffic. Still, all of the subject cities have created extensive networks of exclusive lanes.

Some public transport lanes are fully exclusive, with barriers keeping all other traffic out, except for crossing traffic at intersections. Others, due to roadway space limitations, are "semi-exclusive," designed to accommodate general traffic under special conditions: crossing traffic to or from driveways; parking maneuvers (when a public transport lane separates a parking lane from a general traffic lane); or to bypass a general traffic lane blocked by a truck making a delivery. Since 1991, Brussels has converted many miles of median lanes that trams formerly shared with general traffic into *bandes franchissables*, literally "crossable" or "enterable" lanes. The Brussels Region changed the motor vehicle code to recognize this entity: lanes that general traffic may not use to travel in, but may use to pass a blockage in the general lanes. They are usually raised, roughly paved to discourage traffic use, and separated from the bordering general traffic lane by a mountable curb. Sometimes buses, and in a few cases taxis, are permitted to use the lanes.

When traffic pressure is heavy, semi-exclusive lanes can fail to fulfill their function of allowing buses and trams to pass without hindrance, as drivers are tempted to leniently interpret the conditions permitting cars to use the lane increase the frequency of violations of exclusive lanes. *Moving* violators present little hindrance to public transport; the problem is *stationary* violators. In a study inaugurating Zurich's current public transport priority program, two of the chief hindrances identified were as follow:

- Cars using the tram lanes as left turn lanes, waiting on the tracks for a gap in opposing traffic.
- Accidents on the tram tracks, mostly associated with left turns across the tracks (either from or onto the road with the tracks).

Brussels' recent reports on hot spots includes many caused by violators of exclusive lanes. Besides those identified by Zurich, three other situations were cited:

- When a road has an obvious lack of capacity, frustration sometimes rises to the point that motorists simply take over the public transport lane in order to have an additional discharge lane at a signalized intersection. By queuing up at the intersection, they block the tram. Examples are Rue Royale inside the pentagon and Ave. des Celtes at Merode.
- When a road has long standing queues, cars turning left onto the road from side streets stop in bus / tram lanes half-way through their maneuver, waiting for a gap to enter the traffic stream. Examples are Rue de Stalle and Ave. Rogier.

- When rampant double parking makes it impossible to travel in the general travel lane, as commonly occurs in the famous Louise bottleneck between Place Louise and Place Stephanie.

Faced with violators, one often speaks of the need for enforcement – such is the language of the report *Points Noires*. However, because public transport lanes extend over a long distance, enforcement is not easy, especially when some situations permit cars to enter the exclusive lane. Instead, what is needed are designs that are more self-enforcing.

London, a congested city with enormous pressure to violate bus lanes, is an exception, having an aggressive program of video enforcement. It is helped by the facts that (1) Transport for London (TfL) is responsible for the streets as well as the public transport system of London; (2) TfL is authorized to do its own enforcement; and (3) revenue from enforcement (fines) goes to TfL, covering enforcement costs.

Zurich has used one direct and one indirect approach to make exclusive lanes more self-enforcing. The indirect approach is to reduce traffic, thereby reducing the pressure to trespass. The direct approach is to apply measure that make crossing the lanes more difficult: *making more sections barrier separated* and *imposing left-turn restrictions*, especially where there are high ambient traffic speeds (more risk of accident) or long queues (more risk of trespass). Complementing these measures is the construction of *roundabouts*, which help drastically at lowering accident rates and provide the alternative path needed when turn restrictions are applied. The “barrier” is usually nothing more than a conventional, non-mountable curb. An example is along Tram Line 2. West of Albisriederplatz (away from the city center), there can be long queues in peak hours and high speeds in off-peak periods; there, the median tram lanes are separated by a barrier. Motorists cannot cross the tracks to enter or exit driveways; they have to make U-turns at *roundabouts* at either end of the 600 m long road section. East of the Albisriederplatz, where traffic is slow and quiet, there is no barrier.

Contraflow lanes are naturally self-enforcing, and are therefore strongly favored by STIB’s director of Network Development, Mr. C. Dochy. They are being being built aggressively in the city center, where a dense network of narrow, parallel streets favors the contraflow design. They can also be used on a single street, with public transport operating in an exclusive contraflow lane in one direction and in shared traffic in the other, as on Rue de Trèves on both sides of Place Luxembourg (on either side, the contraflow lanes are going away from the square; buses use shared lanes approaching the square).

Dublin’s *“one-side” design* for its new tram puts both directions of the tram on the same side of the street, with parking prohibited on that side. The bordering tram and general traffic lanes have opposite directions, giving this design the self-enforcing properties of contraflow. In addition, the tram lane next to the curb can use the sidewalk as a platform at stations, limiting the number of platforms that need to be placed in the street. Traffic can still cross the tram lanes to access driveways, so this design is compatible with a commercial area.

Barriers that emulate upstream stop platforms may be as effective if applying a barrier all along the lane is undesirable. To keep cars from using a public transport lane, it is sufficient to prevent them from using the few meters before each signalized intersection. When there is an upstream (near-side) stop, the platform separating the tram lane from the general travel lane makes it unambiguous that general traffic is prohibited, and once the ambiguity is gone, so are the violators. Moving stations to the upstream side of an intersection, or emulating a station with a barrier, is an effective way to keep the tram lane clear.

Double parking is only a problem when it is rampant, which will occur only in busy commercial areas. There, the “obvious” need for traffic to bypass double parked cars and trucks makes it seems necessary to let the tram lane be *franchissable*. However, this apparent “need” is deceptive. If barriers and installed, the double parking will disappear, because motorists will only double park if they believe they aren’t blocking traffic. Of course, deliveries must still be accommodated in commercial areas; but cities have found many ways to accommodate deliveries other than by allowing double parking, such as delivery zones or restricted delivery times.

Bus lanes, like tram lanes, can be put into completely separate roadways, as along Brussels’ Parc de Cinquantenaire and Ave. Eugene Plasky. On wide streets, a design now being pursued by STIB’s director of Network Development is to have contrflow outer roadways for bus, one on each side of the street. Parking would take place within the inner (general traffic) roadway, separated from the bus roadway by a 1-meter median for car doors. If the sidewalk can be wide enough, it could be used for deliveries, with the bus lane used for access.

When general traffic is strictly prohibited from a bus or tram roadway, barriers can be used. The STIB report *Filters* describes bus sluices (holes in the road that will trap a small car, but let a wide wheelbase bus pass), gates, moving posts, and the flexible Rozo barrier. However, violations of such exclusive lanes are not frequent, and not likely to lead to significant public transport delays.

APPLICATION TO BRUSSELS

Brussels already has an ongoing, aggressive program of adding exclusive lanes. They have also done forward thinking about ways to prevent general traffic from using roadways reserved for public transport. However, trespassing traffic on many sections of *bandes franchissables* hurts STIB operations substantially, and will only get worse as urban activity grows. STIB’s *Points Noires* report estimates that achieving compliance on six sections now hurt by trespassing would save 400,000 euros per year in operating costs.

> Hoping to solve these problems through conventional enforcement is wishful thinking. These trouble spots – such as the Louise bottleneck and the Ave. de Celtes approach to Merode, need new designs with barriers to make them self-enforcing.
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> On Ave. de Couronne outbound approaching the Grande Ceinture, a new bus lane has been created along the right side of the roadway with a barrier protecting it. To accommodate right turns, the barrier ends before the intersection. However, the physical dimension needs to be better coordinated with the traffic signal timing. The barrier ends a distance that permits 9 cars to queue up in front of an approaching bus. However, a green light is only long enough for 6 or 7 cars to get through. Unless there are plans are to increase Ave. de Couronne’s green time, the barrier should be extended to a point at which no more than 5 cars can queue in front of a bus, so that buses don’t have to wait more than one cycle to pass through.

6 Limiting Traffic on Public Transport Routes

6.1 Confining Traffic on Through Routes

An important part of Zurich's priority program keeping through traffic routes separate from public transport routes. This policy has two parts. One is confining through traffic to routes that don't interfere with public transport; the other is keeping public transport routes off traffic-bound roadways.

Three motorways approach Zurich, but end short of reaching the city. Connecting them are three major axes of through traffic. Zurich manages to confine those through traffic routes to roads that public transport does not use, thereby protecting public transport. Where public transport crosses the through traffic routes, public transport is given priority.

Brussels has major through traffic routes leading toward the center from where the E411, E40 (both sides), A201, and A12 motorways spill their traffic onto surface roads. An excellent application of confining through traffic is on Ave. de Cortenbergh, where traffic exiting the tunnel from the E40 is confined, by means of turning restrictions, for almost 1 km to the Schuman rotary. One block away, STIB routes 12, 21, and 28 enjoy relatively uncongested travel on the parallel street, Ave. Franklin.

Another application is near NATO, where traffic on the A201 / Blvd. Leopold III backs up for more than a kilometer in peak periods. Parallel to it and just a few meters away, Rue Fusée runs freely, carrying STIB lines 12 and 65. Traffic from the A201 is prevented from reaching Rue Fusée, except for STIB buses that can pass a radio-controlled crossbar to a connecting ramp.

APPLICATION TO BRUSSELS

> Through traffic congests the marginal roads of Ave. Brand Whitlock (Grande Ceinture) southbound during morning peak hours between the E40 (at Reyers) and Montgomery Circle, imposing several minutes of delay on three bus routes. Between Reyers and Georges Henri, affecting bus route 28, the problem is overflow traffic from the E40. The E40 has two discharge lanes; because the left lane's merge onto the main roadway of the Grande Ceinture is over capacity, cars try to bypass the queue and use the marginal roadway. This problem can be solved by closing the second discharge lane and prohibiting E40 traffic from entering the marginal roadway. This limitation could be imposed during morning peak hours only.
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> Between Georges Henri and Montgomery, affecting routes 27 and 80, the problem is the very low capacity of the discharge into the traffic circle at Montgomery. Flow on the two-lane marginal roadway, limited by this discharge rate, is well below what could be carried by a single lane. The second lane, in effect, serves as nothing more than temporary queue storage. That second lane should be converted to a reserved lane for bus. At the same time, the very inefficient junction of the roadway with the Montgomery should be reconfigured to increase its capacity. The key is to provide multiple entry / merge points for the traffic coming from the Grande Ceinture. With a bus lane put into place, traffic will be arriving in a single lane, but on arriving at the Circle, it should widen to cover a space for three or more cars. That way discharge capacity will still be as great as it is today with two approach lanes, and perhaps even greater.

6.2 Separating Public Transport Routes from Through Traffic Routes

A corollary of the policy of confining through traffic is keeping public transport routes off of major through traffic routes, unless such routes are fluid. Of course, sometimes this is not possible, such as when a major traffic route is a commercial street that needs public transport service or when there is no alternative path; in such a case, other measures have to be taken to protect public transport from congestion, such as putting public transport in tunnel.

In Brussels, bus line 12 is an excellent example of applying this policy. It winds its way along relatively uncongested small streets from Pl. Luxembourg to Schuman Rotary to NATO and the airport, bypassing several congested through traffic roads (which, as mentioned in the previous section, effectively confine traffic in order to protect the roads used by the bus).

APPLICATION TO BRUSSELS

> Rue Rogier in Schaerbeek, where Grande Ceinture tram line 90 operates in mixed traffic, is the main crosstown through route in the area, with demand far exceeding capacity. Nearby parallel streets have circulation plans protecting them from through traffic, confining through traffic to Rue Rogier. Without any parallel road nearby that could carry tram line 90, it needs to be protected by extending a branch of the premetro tunnel from North Station to where the tram has a reserved lane.

6.3 Street Closing (One- and Two-Direction)

Zurich’s tram network has many short-distance street closings to keep traffic from wanting to use its tram routes. With a good circulation plan, closing a street for a short distance will keep a long section of the street uncongested even if traffic is allowed on the downstream section of the street in order to meet access needs.

In 2002, a 15-year public participation process ended as formal opposition was withdrawn from the decision to close the Limmatquai, on the Limmat River’s right bank in the center, to general traffic, permitting only trams and vehicles with permits (*e.g.,* delivery vehicles owned by local businesses) (Blix, 2002). Referenda related to the closure had failed in 1987, but won in 1999 (following a positive City Council vote) and in 2002. Opponents, including Switzerland’s automobile clubs, argued that parallel streets did not have sufficient capacity to carry the diverted traffic. However, unplanned experiments when construction forced the street to close for several months for in both 1995 and 1998 proved that the neighboring streets fared just fine, swaying both the City Council and public opinion. (These experiments were further confirmed by Blix’s simulation study.) The street closing has reduced tram travel time by about 3 minutes in each direction for two tram lines, and has given Zurich a beautiful site for a pedestrianized street.

Brussels has also closed streets as a way of protecting public transport. The first action of the Region’s VICOM program (1991) was closing the Ave. Louise crossing at Blvd. de la Cambre and Av. Legrand, thereby protecting several tram lines. Officially, Blvd. de la Cambre and Av. Legrand were also closed, but “local traffic” is permitted, an exception that makes enforcement nearly impossible. However, the closure of the Ave. Louise crossing makes Blvd. de la Cambre and Av. Legrand useless as through routes, keeping traffic levels on those roads low enough that they don’t hinder public transport.

Brussels’ most important example is Rue de Luxembourg, where only buses, taxis, and bicycles are permitted in both directions in the block touching the Petite Ceinture. However, violations plague that restricted block, leading to more traffic all along the

Rue de Luxembourg. Stronger efforts can be taken to make the restriction more self-enforcing (e.g., raising and coloring the pavement to indicate that it is an exclusive lane). In addition, because the restricted block has only two entry and exit points for violators, it is a place where enforcement could be applied effectively.

A Brussels Region's recent report on traffic filters (AED, 2005) describes methods that permit buses or trams to use a street but not other traffic. In addition to their use for transit priority, filters can protect a neighborhood from through traffic, and can be part of a plan for a pedestrianized street. A recent traffic plan for St. Josse is designed to limit through traffic, while at the same time facilitating bus transit by giving buses exclusive through movements on a few small sections.

When a street is closed to traffic in one direction while public transport continues to operate in both directions, as on Rue de Trèves, a contraflow lane (discussed earlier) is created.

APPLICATION TO BRUSSELS

> Rue Bailli is the tram network's best known hot spot, serving trams 81 and 82 and bus 54 while hosting a thriving commercial area attracting clients from across the city. A narrow street crowded with cars, its actual through volume is small. Pedestrianizing the street, while permitting continued access for public transport (and for taxis and delivery vehicles for limited hours), would be both a substantial urbanist improvement and would solve a major public transport bottleneck.
>
> *******************
>
> One of the bus network's worst hot spots is on Chausée de Wavre inbound approaching Chasse. The traffic signal at Chasse gives Ch. de Wavre very little green time, permitting only 6 cars to pass each 82-second cycle. Most of the day, the queue is 25 to 30 cars long, imposing a 6 minute delay. Reducing that delay to 1 minute would save about 75,000 euros/yr on STIB's Route 34, plus another 30,000 and 15,000 euros/yr, respectively, for de Lijn and TEC routes.
>
> The long queues there give a deceptive impression that this road carries a lot of traffic. In fact, the traffic volume is so small – only 6 cars per cycle, or 260 veh/hr – that it could readily be diverted. The section between Av. de la Force Aerienne and Chasse can be made one way outbound, with buses permitted to continue inbound in a contraflow lane. Parking, a concern of the local merchants, will still be preserved, as will access to the neighborhoods. The chief detour will take cars (but no more than 6 more per traffic light cycle!) along Av. de la Force Aerienne and Av. des Casernes; this detour, which does not pass along any residential local streets, is already taken by several hundred cars per hour to avoid the long queues on Ch. de Wavre.

6.4 Signals for Metering Traffic Locally

Where a section of shared roadway (public transport operating in general traffic lanes) meets a road with either no public transport, or a road section in which public transport is in an exclusive lane, a signal can be used to meter the rate at which traffic is admitted to the shared section in order to keep the shared section fluid. An Eindhoven example is on a road approaching the older part of the city, where a bus lane ends where the road becomes narrow. There, a traffic signal lets only a few cars pass per minute, keeping the narrow, shared section of the road fluid. That causes a queue at the metering signal, which the bus bypasses thanks to the bus lane.

This principle can be generalized to limited inflow from any section of lower traffic sensitivity to one of greater sensitivity. An example from Zurich is where the Sihlquai, which has no public transport, joins Limmatstrasse just before the main railroad station where several tram lines cross and intersection capacity is critical. A traffic signal deliberately limits the outflow from the Stillequai, causing a long queue on the Stillequai, but keeping traffic volume around the main railroad station manageable.

APPLICATION TO BRUSSELS

> At the stop Parnasse (intersection of Av. du Throne and Ch. de Wavre): limit green time for Ch. de Wavre outbound in order to keep the section from Parnasse to Place Jourdan fluid, helping routes 34 and 80. The upstream section of Ch. de Wavre has no public transport service.

Opportunities for applying traffic metering may require circulation plans that divert through traffic from public transport streets for short distance. Where the diverted traffic rejoins the public transport street, it can be metered, as long as the resulting queue doesn't reach back onto the public transport street. For example:

> A hot spot affecting bus routes 95 and 96 is along Av. de Vise in the Relais – Arcades – Keym section near Watermael station, where railroad underpasses create a bottleneck. Circulation plans and traffic metering can be put in place to protect the section. At the northern end of this section, Av. de Relais can be made one-way northbound from Av. de Vise to Ch. de Boendael, with a southbound contraflow lane for buses. A signal at Relais / Vise would then limit the amount of traffic permitted on Av. de Vise southbound, shifting the queue onto Av. Gilbert and Ch. de Boendael. Near Pl. Keym, the streets are wide enough to permit a northbound bus lane that would allow buses to bypass any queue, with a metering signal placed where the bus lane ends shortly before the underpass.

7 Queue Management

Urban traffic is full of queues. Delay is proportional to queue length and duration. Surprisingly, however, traditional traffic control methods are ignorant of queues.

In contrast, Zurich's traffic control system takes a direct approach to queue management. It includes queue length estimation; planning for queue formation; using queue length to trigger green starts; and using queue length to trigger green ends.

7.1 Vehicle Counting and Queue Length Estimation

Zurich's traffic control logic uses detectors to count vehicles approaching and leaving an intersection; the difference is the queue length.

The traditional problem with queue length estimation is the need to correct for drift, resetting the system state. Otherwise, undercounting departures by, say, 1 vehicle per minute will result in overestimating queue length by 60 cars after an hour.

When a queue dissipates, it is not difficult to detect that there is no queue; a gap in departing traffic reveals the absence of a queue. Therefore, on approaches that are not congested, resetting the system state to prevent drift is easy.

On approaches with persistent queues, drift is more of a danger. Zurich deals with that by comparing inputs from multiple detectors, using conservation logic, to reduce the chance of data errors. They claim that verification studies have shown their estimates to usually be within 1 or 2 cars of being correct.

7.2 Coordination and Buffers

As mentioned earlier, Zurich's control system can be looked as moving platoons through successive intersections. If platoons have, for example, 8 cars, smooth operation will require a buffer, *i.e.*, queuing space, for 8 cars, plus a few more to accommodate irregularities. If intersections are close relative to the platoon size, the need for a buffer can be reduced or eliminated by coordinating their green times (green wave) so that car can pass through the second intersection without queuing. Coordinated intersections have the same cycle length.

Zurich's control program divides streets into cells of 1 to 3 closely spaced intersections. At cell boundaries, road sections are long enough to serve as buffers. Each cell is programmed independently and as a unit, including a fixed cycle length and stage transition logic that responds to a multitude of conditions, including public transport vehicle detection.

7.3 Limiting Queue Length at Queue Jump Lanes

A queue jump lane is a separate public transport lane of limited length ending at an intersection stopline. As long as the queue is shorter than the length of the queue jump lane, the bus or tram can bypass the queue; but if the queue reaches beyond the length of the queue jump lane, the bus or tram will be prevented from entering its lane. To make effective use of a queue jump lane, Zurich's traffic control program estimates the queue length and compares it with the buffer space, *i.e.*, the length beyond which entry to the queue jump lane would be blocked. If the queue length approaches its buffer length, green time for the approach is increased until the queue length is at a safer value. An example is on Klosbachstrasse approaching Kreuz Platz, where a queue jump lane serving tram 15 provides buffer space for about 12 cars.

7.4 Preventing Blockage

Just as an upstream queue can call for more green, the detection of a downstream queue can call for ending green in order to prevent the intersection from being blocked. Zurich's traffic control system checks for downstream queues in both the general traffic lanes and on tram tracks, the latter to prevent a tram from blocking an intersection when the track ahead (usually at a station) is not clear.

7.5 Pre-Signals

A pre-signal is a signal upstream of an intersection intended to hold back a queue. Usually its timing is coordinated with the main signal in such a way that the pre-signal does not limit capacity or increase delay. An example just installed in Brussels in on Ave. de Couronne inbound approaching the Grande Ceinture, where a pre-signal holds back the queue so that buses can move from a central bus lane to the curb, where the bus stop is located.

7.6 Limiting Pedestrian Blockage

When a lot of a road's traffic is turning right from a lane used by buses, pedestrians can block the right turn flow, keeping the right lane (which the bus uses) from flowing. One solution, used effectively in Paris near Place St. Michel, is to move the crosswalk away from the intersection, leaving the distance between the intersection and the crosswalk as a buffer in which turning traffic can wait while pedestrians cross without blocking the street the turning cars came from.

APPLICATION TO BRUSSELS

More will be written in later chapters about systematic methods for managing queues. At this point, it is important to point out how important queue management is to controlling Brussels' traffic.

> *Preventing Intersection Blockage:* On crowded streets like the Grande Ceinture, intersections are routinely blocked as green is given to approaches in spite of a downstream queue. Cars advance, blocking the intersection, thereby wasting capacity and causing a lot of unnecessary delay.
>
> *Balancing Competing Needs:* In traditional traffic control, the only thing known about a queue is whether it exists. During periods of the day that queues persist from one cycle to another, delays can become enormous without the control program being aware, or correcting it. For example, where Ch. de Wavre crosses the Grande Ceinture, queues often develop that make buses (and cars) wait up to 4 cycles to pass. A control program oriented to public transport priority would not allow that to happen; by adding only 4 or 6 seconds to the cross street green times, those queues could be prevented, without hurting public transport on the Grande Ceinture.
>
> *Preventing Upstream Blockage:* Often, letting the queue length pass a certain point causes a quantum leap in public transport delay. It could be when a queue blocks a queue jump lane, or when a queue blocks a stop. Detecting that should prompt an increase in green time to reduce the queue.

Here are some specific examples for application of pre-signals and managing pedestrian blockage.

> At the Etterbeek Station, pedestrians crossing between the train station and the tram station block right turns from Ave. de Couronne inbound onto the Grande Ceinture.

The blocked cars, in turn, keep buses from getting into the bus stop just upstream of the intersection. The effective functioning of the new pre-signal at this intersection demands that the right lane be cleared out every cycle – something often prevented by pedestrian blockage. The solution is to move the crosswalk to the far side of the tram platform, away from the intersection.

****

Tram line 82 heading from Montgomery toward Place Flagey crosses a narrow bridge over the train tracks just before Ave. de Couronne. On the bridge, the tram shares a lane with traffic and is often blocked by queues (especially if cars are turning left). Before the bridge, the tram is in its own lane. A pre-signal is needed just before the bridge to prevent queues from forming on the bridge, giving the tram an effective queue jump.

8 Priority at Traffic Signals - Zurich

8.1 Predefined Stages and Transition Rules

Zurich’s traffic control logic uses predefined stages, where a stage is a set of traffic streams having green concurrently. Clearance times are two-dimensional (they depend not only on which stream is losing the green, but also on which is getting the green) and are enforced by clearance logic. Minimum green times apply to vehicular and pedestrian traffic streams. Otherwise, transition between stages can be freely programmed to follow any desired logic, using inputs such as gap detections, public transport detections, and queue length estimates. Cycle lengths are fixed, but transitions within a cycle are flexible based on detections, making control “fully actuated.”

Compact intersections allow for short pedestrian clearance times, making the system able to respond quickly to a public transport priority call.

Zurich’s control system has two unique features. One is short, tram-only stages. Typically, a tram running along a street has its green concurrently with the general traffic on the street. If a tram calls for green while the cross street is running, if the cross street hasn’t had most of its green yet, the cross street’s green will be terminated, a short (5 s) tram-only green will appear, and then green will return to the cross street. This tactic prevents the street’s minimum green and clearance times from coming into play, allowing a quicker return to the cross street. This tactic wastes capacity by giving green to the tram alone; however, at intersections operating below capacity, that is less of a concern than trying to return quickly to the planned sequence in order to prevent queue imbalances.

The other is that tram signal are held in red. When the traffic stream parallel to a tram has green, the tram signal is not automatically turned green; rather, it is held in red until the tram is detected. The start of green is timed so that the tram has to slow down a bit; that is a deliberate safety measure to prevent trams from speeding. However, it makes for somewhat of a jerky ride as trams decelerate (but not to a stop) and then accelerate again at every intersection. Another way of preventing speeding might be possible without the jerks.

8.2 Public Transport Detection and Response

Three to five public transport detectors are used on each approach. Part of the reason is to have some redundancy in order to help filter out bad calls. One or more of the detectors may trigger a call for a stage change, depending on the detector location (how many seconds upstream) and the state of the controller. Every approach also has an exit detector to cancel requests.

Some detectors are antennas used to decode messages. For example, when a tram has an upstream (near-side) stop, the closing of the doors triggers a message; a communicating detector is used to receive this message and call for green.

The controller will respond according to logic programmed; depending on the situation, it may extend the current green, insert a short public transport-only stage, or switch to a stage that includes public transport and other traffic streams. When there is an upstream stop, detection before the stop is used to put the controller on standby.

The controller will switch to, or remain in, a state from which it can quickly respond when the door-closed message is received.

Advance detectors sometimes trigger a stage change favoring the cross street and the crosswalks that allow pedestrians to cross to the central tram platforms. Such a change is made early enough that by the time the tram arrives, the stage has changed to favor the tram.

When a tram shares a lane with general traffic (as will soon be the case after the Limmatquai is remodeled; note that general traffic here will be limited to vehicles with special permits), the stage transition logic focuses on clearing the queue from the tram stop.

To prevent public transport bunching, if three public transport requests have been acted on in a short period (60 to 90 s), further public transport requests will be inhibited for the next cycle.

8.3 Outcome

The combination of measures that protect public transport vehicles from general traffic queues and very responsive actuated control means that public transport vehicles have virtually no delay at most signalized junctions.

One significant exception is approaching major transfer stations (Bellevue and the Main Railroad Station), where trams are delayed by each other because of lack of station capacity.

Another exception is when there are conflicting bus or tram lines at intersections carrying a lot of traffic; there, exclusive lanes keep trams from having delays caused by queues, but response to tram requests may be limited or completely absent. An example is Schaffhauserplatz, a five-leg junction with tram lines on four legs, with each leg carrying one entering tram every 3.75 minutes. With such a volume of trams, every signal cycle is likely to have one or more trams, often with conflicting requests. Therefore, tram detections do not trigger any change to the normal cycle (???). Still, by keeping the cycle relatively short, signal delay is limited. For a tram in an exclusive lane, average signal delay is given by $0.5Cr^2$, where C = cycle length and r = fraction effective red time. (This is the same formula for average pedestrian delay.) Therefore, shortening the cycle reduced delay. With a 72 s cycle and green time ranging from 20% to 40% (depending on whether the tram movement is a left turn), average delay will vary between 13 and 23 s.

9 Adaptive Signal Control and Signal Priority in Dublin

9.1 Fixed Time versus Adaptive Control

Most cities accomplish areawide traffic control using fixed-time programs based on historic, steady state traffic volumes, usually with the goal of providing progression (green waves) to heavier traffic movements. In the U.S., those plans frequently include a small degree of local actuation; for example, a side street may be allocated 20 s, with an option of reducing that to 14 s if the side street traffic clears early, with the time saved causing an early return to the main street's green. Such an arrangement is not conducive to public transport priority, because interrupting a cycle to give green to a public transport movement can disrupt the entire coordination scheme. public transport priority applications based on such fixed time plans are usually limited to allowing small green extensions, and sometimes small red truncations. The smallness of the changes allowed means that public transport delay reductions sometimes average only 3 s per intersection.

To make a fixed time plan responsive to overall traffic conditions, many cities use different plans by time of day (a.m. peak, midday, etc.). Still more advanced are cities that use system detectors to estimate overall levels and orientations of traffic flow, and use this information to choose from among a library of fixed time plans.

In the last twenty years, a new approach to urban traffic control has been developed called "Adaptive Control," whose main feature is that feedback from detectors is used to regularly update, by re-optimizing, the control plan. Only three such systems have seen application on a broad scale: SCOOT (developed in the UK), SCATS (Australia), and SPOT-Utopia (Italy). Experimental systems that have been applied only in government-funded tests include PRODYN (France), RHODES (U.S.), and OPAC (U.S.).

SCOOT and SCATS use the simplest form of adaptive control: optimizing a steady-state plan based on recent traffic counts. They calculate a new fixed time plan at regular intervals (say, every 5 minutes) based on recently measured traffic flows, applying some smoothing algorithms to make transitions easy. That makes the control plan responsive to the general flow patterns, but it does not meet two needs for public transport priority control. First, it results in a plan that does not possess the flexibility needed to respond to public transport requests. Second, even when a public transport vehicle's approach to an intersection is imminent, the fact that a steady-state plan is being create based on average flow rates means that information about the particular space-time location of individual public transport vehicles cannot be processed.

SCATS has no public transport priority feature. SCOOT has public transport priority as an added feature, much like public transport priority added to fixed time control, with limited green extension and red truncation. This feature has been applied with some success in London and several other UK cities; however, because of the same limitations that occur when priority is added to fixed time control, it does not achieve (or even attempt to achieve) near-zero delay for public transport.

9.2 Signal Priority in Dublin

As mentioned earlier, Dubin’s signal priority program is new, and is limited to the two new tram lines. On one of those tram lines, the tram operates along a main road in exclusive lanes on one side of the road. On the other, a downtown street has been dedicated to the tram, simplifying junctions where the tram crosses streets.

To give priority to trams, the city traffic control staff developed a program at the system level that takes intersections out of SCATS control when needed for public transport priority, intervenes to make the public transport phase green, and then returns the intersection to SCATS. When a tram is detected approaching an intersection, it is first determined whether normal SCATS control will result the tram getting a green. If so, no further action is taken. If not, the signal is removed from SCATS control and governed by a locally coded program that changes the stage to favor the tram until the tram’s exit is detected; it then transitions back to the stage called for by SCATS, and finally returns to SCATS control.

This system is very effective, with trams experiencing near-zero traffic delay. On the tram line on which the tram follows a main street, the main street has green a majority of the time, and so often no priority interruption is needed. When a priority interruption is called for, the main street gets green as well as the tram. Many of the side streets have so little traffic that they recover easily on the next cycle.

One exception to this priority policy is where the tram line operating in its own street crosses a major arterial, O’Connell Street. No priority is granted, and delay sometimes exceeding 60 s. There is a station shortly before O’Connell Street, and often trams leave that station, only to advance 30 m and then wait for a nearly minute. If it not possible to adjust the signal to match the tram’s arrival, a second-best solution is to match the tram departure from the station to when it will be given green. At least that will reduce waiting time for passengers at the O’Connell Street station.

10 Queue Management and Signal Priority with Predictive Control in Eindhoven

SPOT-Utopia is a traffic signal control program for a city or smaller area, developed originally at the Polytechnic University of Turin, and later commercialized by its current owner, Mizar Automazione SpA of Turin. It was first applied in Turin, which continues to be the program’s largest installation and testbed for innovations. Unlike other adaptive control programs, public transport priority was part of the motivation behind SPOT-Utopia. It has been applied in many other cities in Italy, and in several cities elsewhere in Europe (Turksma). Peek Traffic is the vendor responsible for SPOT-Utopia’s distribution in Europe outside Italy.

In the Netherlands, Eindhoven has SPOT-Utopia’s largest installation, along an important bus route. Before SPOT-Utopia, intersections there had the typical Dutch fully-actuated but independent control, including priority for buses. Actuated control means that detections (of both cars and buses) trigger state changes based on transition rules that are applied very frequently (e.g., 10 times per second). Actuated control with absolute priority gave buses near zero delay, but did not manage capacity well and sometimes resulted in long delays for general traffic. Tests show that the SPOT-Utopia system preserved the near-zero delay for public transport, but by managing queues and coordinating signals, it reduced general traffic delay by 17%.

SPOT-Utopia uses several principles and algorithms for urban traffic signal control that seem promising (Turksma, Peek Traffic), and that are analyzed in the following section. Most of these principles and algorithms are not unique to SPOT-Utopia; some have been implemented in the experimental urban traffic signal control products mentioned earlier, and other form part of traffic control schemes studied in simulation studies by various researchers (Janos and Furth; Wadjas and Furth). Therefore, this analysis is not meant to be an argument for or against any particular software product, but rather an analysis of the principles of the advanced traffic signal control algorithms found in it.

10.1.1 Predicting and Optimizing with Rolling Horizon

The essential logical framework used by SPOT-Utopia, as well as by the experimental programs RHODES, OPAC, and PRODYN, is to predict traffic flows and optimize for the flows expected in the next few minutes (SPOT-Utopia uses a 2 minute horizon). For general traffic, this approach, sometimes called Predictive Control, is obviously superior in principle to optimizing for what passed in the previous five minutes. And for supporting public transport priority, it holds many advantages over the optimize-for-the-past approach. For this reason, it has also been applied (independent of SPOT-Utopia) to support new light rail lines in Salt Lake City and in Houston.

To support predictions about traffic, each intersection informs its neighbors what its signal plan is for the next horizon. Neighboring intersections use this information to predict arriving flows. Intersections also inform their neighbors about queue lengths; together with the signal plan, that permits a neighboring intersection to determine whether its own discharges might be blocked by downstream queues.

Predictions about public transport vehicle arrivals are made using a longer time horizon, about 5 minutes. Using a Kalman filter, the public transport travel time profile is constantly updated so that predicted arrival time will reflect recent conditions. Location information can come from any source, including communication with an Automatic Vehicle Location system and in-street detectors. (STIB has an AVL system that could be used for this purpose.) public transport arrivals are predicted for a window of time, with a triangular distribution; the width of the triangle decreases as the vehicle gets closer, reflecting greater certainty. In a common configuration, real or virtual detectors are placed 20 s upstream of an intersection so that final control actions are made at the right moment.

Following the “rolling horizon” scheme, the optimized program is implemented for only a short time – 3 s in the case of SPOT-Utopia – until the next optimization is done.

Predicting and optimizing offers several advantages to public transport. Individual public transport vehicle arrivals can be predicted, and predicted far enough in advance that signals can be readied for their arrival, rather than face a last-second request to change. Green waves can be developed for public transport vehicles over a short time horizon, updated frequently to account for unpredictable dwell time and signal delay times.

10.1.2 Fixed Stages, Transition Logic, and Priority

SPOT-Utopia’s state transition logic uses fixed stages. Transitions are made in the course of applying the optimal control plan, updated every 3 s.

The optimization evaluates every possible transition plan using a cost function and chooses the best. Branch-and-bound is used for the nearer term (first 45 s or so), and heuristic methods are used for the rest of the 2-minute planning horizon in order to reduce complexity and speed processing time. The cost function accounts for delays in the approach queue, delays due to downstream queues, penalties for exceeding queue length thresholds, and smoothing penalties that will be described later.

Control can be tuned by altering a number of weights and switches. One switch is for public transport and emergency vehicle priority. At the “no priority” level, a public transport vehicle has the same weight as a private vehicle. With medium priority, a public transport vehicle counts as about 25 private vehicles; the delay-minimizing cost function will then naturally call for stage transitions favoring public transport. With absolute priority, meant for emergency vehicles and strongly disruptive to general traffic, the road serving the priority vehicle gets steady green to clear it of all queues.

10.1.3 Self-Organizing Local Control: Coordination and Queue Management

SPOT-Utopia uses a self-organizing principle, allowing each intersection to seek its own optimum, but communicating with neighboring intersections both directly (by transmitting information about its current state, queue lengths, and plan for the next two minutes) and indirectly (by sending traffic). Coordination occurs “organically,” *i.e.*, without being imposed from a higher level. Under heavy traffic flows, as neighboring intersections try to take accommodate the flow profile coming from each other, they naturally converge to a common cycle. Long sections that can serve as a buffer holding a large queue, and where platoons disperse, becomes a natural place for decoupling. (However, SPOT-Utopia’s logic does not, at present, include platoon dispersion.) On the other hand, when flows are small, SPOT-Utopia’s framework will naturally lead to allowing each intersection to have as short a cycle as it can, without coordination, which for low flows is the efficient means of control.

Allowing coordination to happen organically can lead to unexpected yet efficient modes or coordination that probably would not be part of any “hard-wired” coordination scheme. For example, at a spot known to traffic engineers as Heetmaplein in ’sHertogenbos, two intersections 60 m apart find that optimal operation during certain flow conditions has a cycle length ratio of 2:3 (e.g., 60 s and 90 s). One of the intersections has 4 legs, and needs to operate at a longer cycle in order to accommodate greater flows and a greater number of movements; the nearby 3-leg intersection, however, uses a shorter cycle length because of the limited queuing buffer between the two intersections.

A signal system that is self-organizing has the ability to recover from disruptions. That makes it an especially attractive for public transport priority, which can disrupt any “ideal” coordination plan. Being self-organized means that the system will naturally come back into coordination.

The framework of local optimization with neighbor-to-neighbor communication is well suited to queue management. When an intersection with a long queue on a particular approach optimizes its own signal plan, it will plan to give a longer green to the queued approach. The next downstream intersection will be informed of that signal plan, and thereby know that a large flow is coming, which it will then accommodate in its own timing plan, by planning for a longer green for that flow. The next intersection downstream, in turn, will learn about that longer planned green, propagating information downstream and thereby clearing the queue.

Likewise, when a queue that cannot be discharged begins to block a segment, information communicated to the upstream intersection will result in its granting less green time to traffic streams that would be blocked. As queues on those streams’ approaches build, the upstream intersection is informed and can use that information to limit the green time of its streams that feed the blocked approach. Thus, nearest-neighbor communication allows information about queues to propagate upstream as well as downstream.

Research has shown that simple, independent, fully actuated signals are also self-organizing, to a degree. If one intersection sends large platoons of traffic to its neighbor each cycle, and the neighboring intersection has the standard actuated control algorithm of holding a light green until a gap is detected, the signals will naturally synchronize. That makes actuated signal systems well suited to recovering from a priority interruption. However, in this system, the queues themselves are the means of communication – that is, a downstream intersection doesn’t know that traffic is coming until it’s there. Therefore communication only becomes strong when queues (or, at least, platoons) become large. Simple actuated control can also communicate upstream. A downstream detector is used to detect a queue that will block output, and based on this input, an actuated signal can be programmed to end a green period.

SPOT-Utopia’s algorithms apply the communicating, self-organizing principles of actuated control (although some of them, such as gap detection, are applied indirectly). In addition, its system of communicating locally optimized signal plans for a 2-minute planning horizon should, at least in principle, make the system even better coordinated and self-organizing. The city of Eindhoven has been an informal laboratory for testing these two approaches. The fact that SPOT-Utopia's system reduced delays there attests to the effectiveness of its enhanced communication in coordinating signals, without losing the benefits of local optimization.

10.1.4 Global Adaptive Control as a Guide

When traffic flows in two directions, coordination along an arterial or in a small area can be unstable, oscillating between two or more solutions. For example, the eastbound traffic flow may lend itself to a 60 second cycle, while the westbound flow calls for an 80 second cycle, and optimal control, evaluated every 3 seconds, may oscillate between the two.

Typically, adaptive control algorithms avoid oscillation by either including a penalty term in the cost function for a large change from the current plan, or by limiting the extent of change from the current plan. (The latter seems in principle to be a poor idea, since it can prevent valuable but large changes from occurring; the former will permit a large, valuable change.)

SPOT-Utopia uses an additional means to ensure stability. Collecting information from controllers throughout the network, it performs adaptive control optimization to find an "optimal" global, steady-state control plan. This plan is not imposed on the local controllers; however, it is communicated to the local controllers, and the cost function includes a cost for deviating from this plan. A stability monitor adjusts the weight given to this penalty, increasing it when it seems that the system might become unstable.

If traffic runs smoothly, this adaptive control feature will make the signal control follow the global adaptive optimum. Local controller preferences, for example, to have a smaller cycle at an intersection with less traffic than its neighbors, will be overridden because they don't offer enough additional benefit to offset the penalty of deviating from the global plan. On the other hand, an expected disruption can make the local optimum dominate, such as when a public transport vehicle arrives during what would be a red period, or if large queues have formed due to either a public transport priority interruption or any other reason (e.g., a temporary blockage due to double parking).

Another interesting research question is how often, and under what circumstances, the global adaptive solution dominates.

10.1.5 Detectors, Counts, Queue Estimation, and Parameter Estimation

SPOT-Utopia's algorithms need input from upstream and downstream, but not stopline, detectors. Usually, the downstream detector of one intersection serves as the upstream detector for the next intersection, so that in fact, only downstream detectors have to be installed. Dedicated upstream detectors are needed only on segments on the boundary of the control area, and on internal segments that have large traffic sources or sinks (parking lots, or unsignalized streets with substantial flow) between intersections.

The heavy reliance on downstream detectors is a unique feature of SPOT-Utopia. Their usefulness stems from correlating detector data with the signal state, which is (usually) sufficient to determine the source of the moving traffic; downstream detectors then determine its destination. That way, inflow rates and turning movements can be counted as well as outflow rates.

The fact that sometime two origin approaches can contribute to a destination approach (e.g., westbound left turns and eastbound right turns end up on the same discharge roadway) can confound the estimation process. To reduce uncertainty and improve accuracy, each discharge lane has its own detector.

Every three seconds, SPOT-Utopia's intersection controllers estimate both the number of cars in the queue (the "vertical queue") and the position, in space, of the rear of the queue ("horizontal queue"). Departures are counted using downstream detectors; arrivals counts are communicated from the upstream neighbor as the departure count there. A two-state queuing model is used to determine vehicle position, and thereby locate the rear of the horizontal queue. In a two-state queuing model, vehicles are either standing in a queue with an assumed spacing, or are moving at a given cruise speed.

Queue estimation logic expects some vehicles to "appear" and "disappear" with certain rates (birth and death rates), representing vehicles entering or leaving driveways, parking places, or unsignalized side streets. Parameter estimation logic is used to constantly update the estimated birth and death rates to be consistent with flow measurements at different points.

Every SPOT-Utopia installation demands a fair amount of tuning, making sure externally supplied parameters (e.g., cruise speed) are realistic and that detectors are functioning properly. After tuning, Peek finds that queue length estimates are very accurate, within 1 or 2 cars.

This ability to accurately estimate queue lengths, and the reliance on queue length information on signal control, is a common feature of SPOT-Utopia's and Zurich's approach to traffic signal control, and stands in contrast to commonly used methods of control that know nothing about queue length except to the extent that detectors, usually at the stop line and sometimes at a single point upstream, are or are not occupied.

From detector and signal state data, each intersection's controller constantly updates its estimates of saturation flow rate the turning distribution, using Kalman filters.

10.1.6 Added Actuation Functionality

With its installation in Eindhoven, SPOT-Utopia was enhanced to give it the capability of actuated control at a fine level (1 s or less) using general detector information. Until then, it took the program 3 s to respond to changes detected. With only downstream detectors (standard for SPOT-Utopia), a 3-s gap may not be detected until 4.5 s after that gap has appeared at the stop line. If then the program can't respond for another 3 s, one faces the prospect of traffic held by red signals for 7.5 s, plus a change interval, while no opposing traffic runs. This weakness increases waiting time, and was particularly irksome to Dutch pedestrians, cyclists, and motorists, who are used to very responsive actuated signals.

Dutch traffic engineers at Peek Traffic worked with the program's developers in Turin to add the actuation feature. It allows the controller to respond every second, within the context of the control plan updated every 3 seconds. For example, the optimal plan for the next 3 s may be to hold a certain stage in green, with the option of terminating that stage in favor of a (specified) next stage if a certain condition is met, such as a gap length reaching a certain threshold or a bus passing a virtual detector.

The addition of actuation functionality makes control more efficient in general, and favors public transport priority by reducing response time. Transition logic has allows been extended to include such tactics as returning to the last stage if a bus is detected during an intergreen. At the same time, the Dutch need to serve a greater variety of traffic streams (e.g., bicycle streams) together with their desire for greater flexibility and responsiveness has led to the program's increasing the number of possible stages at an intersection from 10 to 20. These added functionalities are a good sign that SPOT-Utopia is getting the regular improvement that is needed by any control system.

10.1.7 Global Route Management

A feature of SPOT-Utopia used in Turin but not in any Dutch installations is global management of designated critical routes, usually public transport routes. The method of creating the global adaptive signal plans includes logic for limiting traffic on priority routes.

In principle, this approach has an advantage over traffic metering schemed devised for specific intersections, because it results in a diffuse system of traffic metering, with flow rates and impacts optimally balanced over several intersections.

10.1.8 Scandinavian Experience

SPOT-Utopia has been installed in several Scandinavian cities. The consulting firm Sintef is particularly active in studying these networks, both with simulation prior to installation and with field data after installation.

11 Management of the Signal Control System

11.1 Control Program Ownership and Programming

Zurich and Eindhoven exemplify two opposite approaches to managing their control programs. In Zurich, the control programs have all been developed in house by staff programmers, in a standard computer language (Modula). Each intersection has its own control program, containing all the logic for stage transitions. There are also higher level programs for coordinating groups of intersections and for communication and management citywide. The city staff includes several experienced programmers who write logic as needed for improving traffic control. Their knowledge of the city, experience with traffic control programming, and continuing responsibility, together with adequate staffing levels, ensures that careful attention is paid to every intersection's control program, and that enhancements are regularly made.

Zurich's traffic signal programs have been developed in isolation; that is, no other city shares their programs. That presents some drawbacks; for example, they can't share lessons learned, much less computer code, with counterparts in other cities, and it results in a tiny pool of experienced signal control programmers, which may be disruptive if some of their more experienced staff members retire or otherwise leave.

In contracting with Peek Traffic for SPOT-Utopia, Eindhoven has followed a completely different approach. The control program is owned by a vendor. Because SPOT-Utopia is an area-based traffic control method, a standard program for stage transitions is applied to every intersection. The way desired control tactics are specified for an individual intersection is to specify its configuration, stages, and parameter values. This specification process is considerably simpler than writing a control program, and is a joint responsibility of the vendor and local staff. The need for programming is thereby minimized, and responsibility for maintaining and improving the program rests with the vendor. However, city staff can still, with cooperation of the vendor, adjust the way intersections are controlled by changing the intersection inputs.

Either way, the result is a rather complex logic for every intersection, and a lot of attention paid to every intersection's operation.

11.2 Central versus Local Computing and Logic

In Zurich, while control logic is applied for every intersection independently (sometimes with two or three intersections coupled), they have chosen a system architecture in which at computation takes place centrally. Controllers communicate all detections to a central computer, which communicates back to the controller when it should change its signals. That configuration makes the system independent of controller supplier or type, since controllers do little more than communicate with the central computer and change signal indications when instructed. They also perform basic functions for which every controller is pre-programmed such as enforcing clearance (intergreen) times and conflict monitoring.

Zurich's centralized architecture makes it easier for them to manage the system; however, it requires a high quality communication network between controllers and the center. It should be emphasized, however, that while computation is carried out centrally, control logic is applied locally; that is, a separate control program is run for each intersection.

SPOT-Utopia systems such as Eindhoven's use a combination of local and central computing. Local computing is done is a dedicated SPOT "box," a computer installed in the controller cabinet. That makes the system independent of controller type, provided it can communicate with the SPOT box using a standard port. Global optimization is done on a central computer, which communicates with the SPOT boxes at 3 second intervals, receiving such information as signal state, traffic counts in the last interval, queue length estimates, and so forth, and sending back a control (stage transition) plan. A communication network has to facilitate fast communication not only between central computer and local SPOT boxes, but also between neighboring SPOT boxes.

11.3 Monitoring and Data Archiving and Analysis

Every modern control system, including Zurich's and Eindhoven's, includes functionality permitting city staff to monitor intersection and system performance in real time. Maintenance functions, such as detecting a faulty lamp or detector, are also standard.

Less widespread is the ability of the system to log and collect data for archiving, permitting off-line analysis of performance. In Zurich, where city staff are intimately familiar with every intersection, little need for such a capability is felt. They can tell if an intersection's control program is working effectively simply by monitoring its operations. Before / after studies to determine the impact of a change in control plans, or of any other change in traffic, are not routine. When needed, they can play back the monitor data stream to investigate an incident, or for special purpose research.

SPOT-Utopia has some data collection functionality. For example, all public transport passages are logged, and some high level tools exist for calculating performance measures. Users can set high level targets for delay, travel time, and similar performance measures, and run reports comparing performance to targets. Turin is the most advanced in applying these tools.

12 Conclusions

Zurich and Eindhoven present very different examples of cities with superior systems of traffic control to meet societal objectives, including priority for public transport. Brussels is at a position of considering investing in upgrading its signal control and public transport priority systems. What lessons can be applied from the previous analysis?

1. **Effective traffic management *can* resolve most of Brussels' *points noires.***

Reviewing the *points noires* cited in STIB's report in light of the techniques described in this report, I conclude that nearly all of them can be resolved by effective traffic management. Only a few (where pre-metro extensions are needed into Schaerbeek and Uccle) require the investment of building new tunnels. This report offers suggestions for resolving several *points noires*. The Region and STIB should take an aggressive position to eliminate all of the network's *points noires* in the near future.

2. ***Télécommande*'s value depends on traffic control system's ability to grant priority.**

In Brussels, signal priority often goes under the term *télécommande*, which literally means requesting [priority] at a distance. The term can engender confusion, because *requesting* priority by itself is no guarantee of effectively being *granted* priority. The effectiveness depends on how well the signal control system is able to convert such a request into near-zero delay service.

Dublin's system of requesting tram priority is completely outside the ability of its base-level traffic signal control program to deal with. To give trams priority, city staff had to develop specialized control programs. Such an approach may be workable for a few tram lines, but is not practical for an entire public transport network.

In the U.S., several cities that have applied public transport priority within existing rigid traffic signal control systems, which emphasize coordinated control benefiting auto movements. Because of the rigidity of the overall signal control system, delay reductions for public transport have been only 3 seconds per intersection in some cities, questioning the value of the priority system.

Some traffic control approaches are well suited to public transport priority, and others aren't. Brussels needs one that is. Adding *télécommande* to a traffic signal system that can't effectively accommodate priority requests will be ineffective.

3. **To achieve near-zero public transport delay, a traffic control program needs to be flexible and interruptible.**

High level public transport priority performance requires a signal control scheme that is highly flexible and responsive, and that recovers quickly and efficiently from public transport interruptions. Fixed-time control and adaptive control schemes that essentially update steady-state, fixed time plans can provide some delay reduction for public transport, offering small green extensions for example; however, they cannot offer the near-zero delay performance seen in Zurich and Eindhoven.

In Zurich, the needed flexibility is provided by a combination of short cycles, compact intersections that reduce pedestrian clearance time, the option of very short tram-only stages, and an overall approach to traffic management that keeps queues on public transport routes short. (The latter permits the capacity loss caused by the insertion of tram-only stages). Specialized and detailed programming of control rules provides the ability to quickly grant priority and to quickly recover.

In Eindhoven, flexibility and ability to recover come from using locally optimized control with inputs from neighboring intersections, resulting in a system that is self-organizing and therefore well adapted to recovering from interruptions.

4. **Predictive priority offers strong benefits for both general traffic and public transport.**

With Predictive Priority, applied in Eindhoven as part of SPOT-Utopia and also applied in specialized control plans in Salt Lake City and Houston, public transport arrivals are predicted well in advance, and signal control plans adjust in order to be green for the public transport arrival, rather than waiting for a last-second request to change to green. With advanced prediction, the control plan is also adapted to serve competing traffic both before and after the public transport stage, making recovery organic, rather than reactionary.

Zurich achieves a measure of predictive priority by using advance detectors that direct controllers to get into a signal state ready to receive a shorter-term call for public transport green. Its ability to succeed without predictive priority is thanks to its short cycles and small queues. Without a drastic reduction in traffic, Brussels will be in position to benefit greatly from predictive priority.

5. **Effective queue management is critical.**

For intersections facing possible oversaturation – and that probably includes most of Brussels' signals – effective queue management is critical for both general traffic and public transport priority. Neither pre-timed signals, nor conventional actuated signals, nor some adaptive control programs provide the needed ability to manage queues.

Both Zurich's and Eindhoven's traffic control system include queue length estimation as an essential component, and use queue length in their algorithms for selecting control plan. Zurich uses specialized programs at each affected intersection to estimate queue length and to govern responses including traffic metering (limiting inflow) and avoiding downstream blockage (limiting outflow). Eindhoven's system makes queue management part of each intersection's control objective.

6. **Good traffic control isn't cheap.**

The logic and level of programming needed for good traffic signal control demands a *lot* of work. Zurich and Eindhoven have following different paths to achieve the same end. The Zurich option is to have a substantial staff of traffic control engineers and programmers involved in developing and improving the control system. The Eindhoven option is to pay a vendor for control software (representing past development work), and to maintain staff expertise in monitoring the system and developing inputs. With any such software product, it is vital that it be supported by a company that is continuing to improve and update its products.

7. **Effective management requires off-line analysis capabilities, not just real-time monitoring.**

Data collection, archiving, and analysis functionality is essential to managing a system of traffic signals as large as Brussels'. Data collection and analysis capabilities should be able to determine whether the system is meeting its objectives by answering such questions as, How great and variable is public transport delay? What is the intersection throughput? How often are priority requests received, and how often do they result in near-zero delay? How often and where do queues block public transport vehicles? Such a data analysis system should be able to support before / after studies to confirm whether an intervention taken has had the desired effect. It should also be able to support a service quality system for commercial speed and public transport priority as envisioned by STIB’s Director of Network Development.

8. ***Télécommande*** **and traffic signal control must be complemented by regional mobility policies and local circulation plans that keep public transport protected from congestion.**

The ability of a signal control plan to provide good service to public transport in the face of overcapacity is limited. In Brussels, so many of the signalized streets serve public transport routes that options for effective queue management are limited. Regional mobility policies, including limiting parking supply, periphery metering, ending tax incentives, and investments in grade-separated public transport, are needed to reduce traffic to a level that it can be kept fluid, to the benefit of not only public transport but all traffic.

Local circulation plans, including reserved lanes with self-enforcing designs and street closures, are needed at many “hot spots” to get public transport out of traffic queues. Local traffic metering is needed to limit traffic on routes without enough space for dedicated public transport lanes.

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